E-24-685

FINAL TECHNICIAL REPORT

A DECISION SUPPORT SYSTEM FOR THE OUTFIT PLANNING PROBLEM: MODELING AND CONCEPTUAL DESIGN

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Prepared for

DEPARTMENT OF COMMERCE
Contract No. DO–A01–78–00–3074

February 1, 1980

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF INDUSTRIAL & SYSTEMS ENGINEERING
ATLANTA, GEORGIA 30332

50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO.	2.	3. Recipient's Accession No.

4. Title and Subtitle

A Decision Support System for the Outfit Planning Problem: Modelling and Conceptual Design

5. Report Date

February, 1980 (issued)

6.

7. Author(s) Leon F. McGinnis, Jr., and Robert J. Graves (University of Mass. - Amherst)

8. Performing Organization Rept. No.

9. Performing Organization Name and Address

Georgia Tech Research Institute
Administration Building
Georgia Institute of Technology
Atlanta, Georgia 30332

10. Project/Task/Work Unit No.

11. Contract(C) or Grant(G) No.

(C) DO-A01-78-00-3074

(G)

12. Sponsoring Organization Name and Address

U.S. Department of Commerce
Maritime Administration
14th St. and Constitution Ave., N.W.
Washington, D.C. 20230

13. Type of Report & Period Covered

Final (9/77-12/79)

14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

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For many outfit materials, the outfitting can be accomplished in any one of several production stages. The on-unit, on-block, on-board terminology is reflective of these various production stages. It is widely recognized that early outfitting (on-unit or on-block vs. on-board) can have favorable impacts on cost, quality, and time to completion. It is also true that early outfitting requires coordinating the steel and outfitting schedules as well as closer control than is typical with traditional outfitting.

This report describes in detail the outfit planning problem and presents some basic elements of a decision support system for outfit planners. A formal model is developed for the outfit planning problem and the potential use of this model in a decision support system is discussed. The model leads to a difficult optimization problem, and several promising solution strategies are identified. Finally, a program is described for empirical evaluation of the proposed decision support system.

17. Document Analysis a. Descriptors

Shipbuilding, Industrial Engineering, Project Scheduling, Resource Allocation, Network Modelling, Heuristic Optimization

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
Release Unlimited	Unclassified	91
	20. Security Class (This Page)	22. Price
	Unclassified	

(See ANSI–Z39.18) See Instructions on Reverse

OPTIONAL FORM 272 (4–77)
(Formerly NTIS–35)
Department of Commerce

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Final Technical Report
Department of Commerce Contract
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ACKNOWLEDGEMENT

The authors gratefully acknowledge the assistance of an Industry Advisory Panel in this work. The Panel members have generously given their time and effort to discuss current practice and trends in shipbuilding, to critically review the research and to provide suggestions for improvement. While sole responsibility for the research results rests with the authors, we do wish to thank the following individuals:

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1.0 THE PROBLEM

The production of ships is a complicated and complex endeavor which is often compounded by the size, weight and design complexity of the product. The purpose of the following report is to examine in depth one particular aspect of the planning problem associated with ship production. Although terminology is far from standardized in the industry, it is desirable to call the problem under study the outfit planning problem, because this seems to be a widely recognized phrase which conveys to almost everyone in the shipbuilding industry at least some parts of the issues being addressed. In addition, this is consistent with the terminology recommended in a study conducted under the Maritime Administration sponsored research program of the Society of Naval Architects and Marine Engineers [7, 8].

For purposes of defining the problem, ship production requires four factors - facilities, labor, materials and expenses (e.g. sea trial). A useful oversimplification is to say that the materials fall into two categories - hull steel and "everything else." The term "hull steel" is meant to include all internal decks and major bulkheads but could omit, for example, ladders, hatches, etc. Based on this categorization, the production activities can be broken into two distinct groups.

The first, or steel phase activities, encompass all the activities associated with fabricating and assembling the hull steel. In common terminology, this would include all steel related activities up to and including complete ship erection. Note that, at this point, the specific production methods relating to the fabrication of subassemblies, assemblies, etc., are not of concern.

The second group encompasses all the activities associated with fabricating and installing "everything else." Again oversimplifying, these are called the outfitting phase activities. Conceptually at least, the outfitting phase activities could come after the steel phase activities are completed. In fact, there is no need, conceptually, for the completed hull to remain in the ways, so the outfitting phase activities could follow float-off. As a practical matter, of course, this would not be a feasible production method because of the expense of opening up closed compartments to land equipment or to install piping, etc.

This is obviously an extremely oversimplified view of the shipbuilding process. It does, however, capture much of the traditional concept of outfitting as a "successor function" [6]. That is, production often has been treated as two distinct phases with very little interfacing of the steel and outfit activities.

Recognizing that it would be uneconomical or technically infeasible to completely separate these two phases of production, a very complex outfit planning problem arises:

(1) specify alternative organizations of the outfit phase activities;

(2) determine which outfit phase activities are to be pulled forward into the steel phase activity schedule;

(3) integrate the scheduling of steel phase activities with those outfit phase activities which have been pulled forward.

The attempt to integrate outfit and steel phase activities has been referred to as preoutfitting by some shipyards. In this report, preoutfitting will be used as a generic term to describe outfitting phase activities which are performed prior to float-off. Those yards that use the term preoutfitting generally have a much more specific definition, which is reflected in this report by a more specific set of terms to describe preoutfit options, i.e.

alternative methods for the implementation of preoutfitting.

Even a small sample of U.S. shipyards reveals that there are no generally accepted methods or guidelines for preoutfitting. Indeed, there is no universal acceptance of preoutfitting as a normal production practice (except for a few obvious and fairly essential items). Perhaps one reason for this situation is the difficulty of evaluating the benefits and costs associated with increased levels of preoutfitting activity.

In the first place, there are no standard methods for reorganizing outfit activities for preoutfitting. Obviously, the manner in which the preoutfit activities are defined has a tremendous impact, not only on their cost, but also on their interaction with the hull steel activities.

Although almost every shipbuilder seems to feel that preoutfitting can reduce costs, there does not appear to be much hard data to support this position. Further complicating the problem is the assessment of the impact of preoutfitting on the steel erection schedule. It is very difficult to determine if any delay in the latter is acceptable and if so, how much.

Finally, there is the difficulty of determining the criterion by which the benefits of preoutfitting should be measured. Traditionally, one of the overriding concerns was with maximizing the rate of steel erection. If this is to be the goal, then the opportunity for preoutfitting will be limited. If, however, the goal is to minimize the total production time, much more preoutfitting may be desirable.

What is needed is an analytic methodology for assisting shipbuilders in making outfit planning decisions. Currently, no such methodology is available. This report summarizes the first year's work under a MarAd-sponsored research contract which has as its ultimate goal the development of such a methodology.

1.1 ASSESSMENT OF STATE-OF-PRACTICE

Shipyard production planners currently make decisions to assign particular work elements to preoutfit or outfit categories according to certain decision practices. A necessary component of the current research is an assessment of the state-of-the-practice including the factors which directly affect these decisions. The contents of this section result from telephone interviews and on-site visits encompassing four major U.S. shipyards.

1.1.1 Initial Findings

Initial findings reveal semantic differences with respect to shipyard use of the terms preoutfitting and outfitting. Further, the different production methods of the yards are coincident with different levels of achievement of preoutfitting. It is not clear at this stage whether these differing production methods are fundamental to the differing achievement of preoutfitting.

The semantics problem arises both in terms of the timing of a particular event and in the types of events to be counted. Some shipyards consider preoutfitting to cover the time span prior to launch while most others use erection as the demarcation time. Representatives from one yard consider the phrase preoutfitting to be much too limited and prefer to use terminology from Japanese shipyards including "on-unit," "on-block" and "on-board."

Outfitting on-unit implies the assembly of some interim product which consists exclusively of outfit materials. Outfitting on-block, on the other hand, is the installation of outfit components (may also be units) onto a hull structural assembly or block prior to its erection. Finally, outfitting on-board implies the installation of outfit components or the performance of outfit tasks during and after the ship erection process. This concept is illustrated in Figure 1.1.

Other terms that reflect what might be viewed as specialized approaches to outfitting include "packaging," e.g. the racking of electronics on a foundation for installation as a unit, and "palletizing," e.g. the temporary mounting of related units on one plate for subsequent separation and final placement.

In general, the tasks included in the phrase preoutfitting are those associated with piping, fixtures, ducting, wiring, electrical equipment, machinery, etc. but distinguished from bulkheads, decks, inner bottom piping, shell assemblies, etc. However, when various performance measures for production planning were examined with specific reference to percentage of preoutfitting achieved, the measurement problem and the semantic problem became confounded. Some yards measure preoutfit percentage by expenditures against budget in certain accounts although these accounts may also reflect hull steel work. Thus, a relatively high preoutfit percentage can typically be reported. Other yards might include cost elements for boilers and power plants in their estimation of percentage preoutfit. Thus, the lack of compatibility between yards on this single measure at this time is noted. On-site observation of several yards revealed a wide disparity between preoutfitting accomplishments. Because specific jobs in a yard at particular points in time may suffer from certain material delays or other conditions which do not reflect a normal level of preoutfitting, these single observations should be evaluated with caution.

1.1.2 Organization for Production Planning and Production

Most of the yards contacted produce ships using shipways and a pyramid

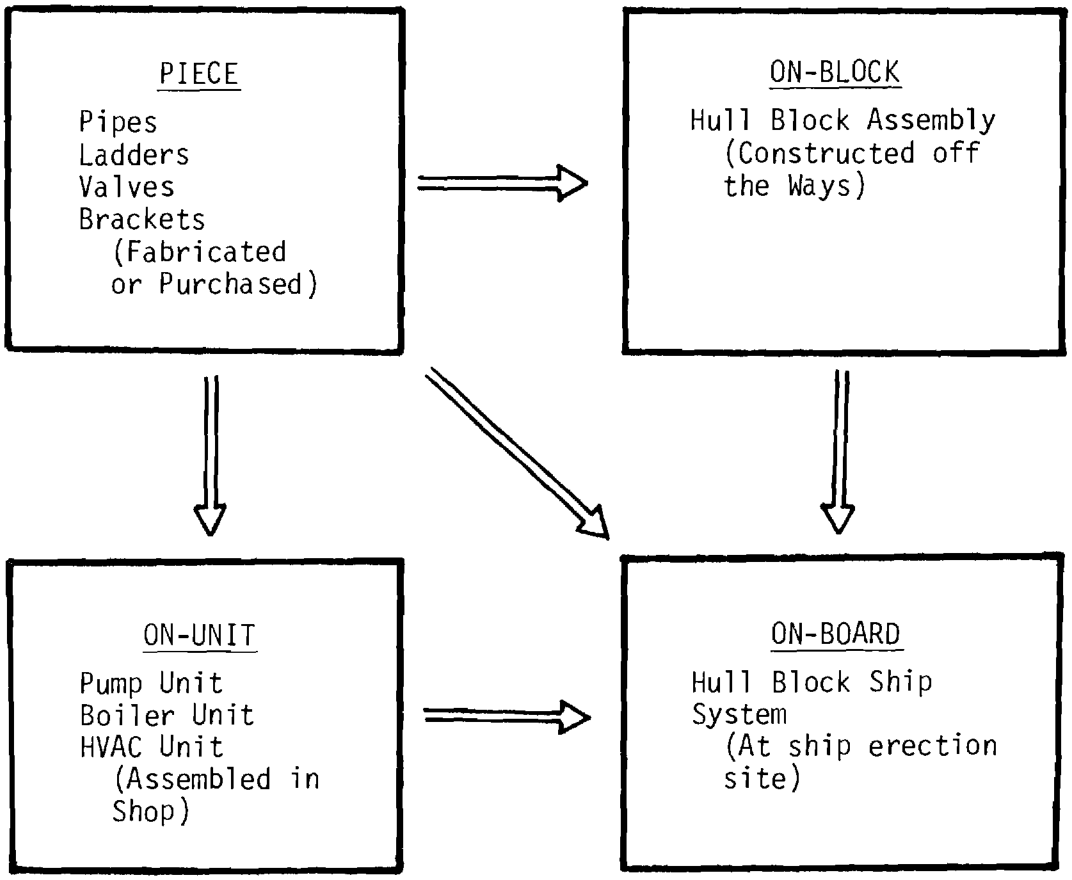


Figure 1.1 Conceptual Stages of Outfitting

type assembly style. One yard was a notable exception with a sophisticated rail and transfer car translation system and a style of production characterized by subassembly aggregation into major ship sections. In each type of yard, fabrication shops for steel, sheet metal, piping and electrical components fed the various assembly and outfitting areas with shapes and partially fabricated components for installation. Launching is typically achieved by means of a platform or floating drydock. After launch, the ship is moved to a wet dock area for final outfitting, testing, painting, etc.

Personnel organization seems quite varied. One yard was organized by labor craft, with a Superintendent over each craft, a Shipbuilding Superintendent and a Wet Dock Superintendent. Another yard was organized by profit centers which included steel fabrication, boiler shop and then production trades with a Supervisor in each center. Most of the yards providing information were organized along the lines of the former description.

Another pertinent facet of shipyard organization is the way in which initial or milestone planning is distinguished from implementation or production scheduling. Most shipyards had one group performing a milestone planning function at a strategic planning level as part of the proposal activity for contracts. This planning group usually relied upon cost data from other groups in performing its function. After contract award, another group assumed responsibility to implement the plans and control the production process, i.e. to perform at the tactical level. This attribute of shipyard organization is important and so the phrase <u>milestone planning</u> is used in this report to describe activities in the former area and the phrase <u>production planning</u> is used to do the same in the latter area. Since these phrases may be at odds with the titles of groups in various shipyards, the reader is urged to note the general intent of the distinction and the functions performed in each area.

1.1.2.1 Milestone Planning

The milestone planning activities are those related to the fabrication and production process but which occur as part of the concept design stage. In most yards, these activities include the setting of major milestone events, the sourcing and scheduling of material and equipment, the planning for resource loadings, and the initial breakdown of the ship into major producible elements. Plans developed at this stage generally guide the actual production process and hence significantly impact the preoutfitting capacity in production. For example, within manpower constraints, a short time span between keel laying and launch will likely limit the amount of preoutfitting that can be done. A launch date or erection date which precedes arrival of material, e.g. piping, will cause these components to be outfit rather than preoutfit. Similarly, significant fabrication prior to assembly and erection can impact the in-process storage capacity of the yard until keel laying, with fabricated sections then moving to erection.

These milestone planning activities typically occur coincident with the Definition or Contract Design stage of the U.S. Navy conventional procurement system in large shipyards where prior stages of design are primarily Navy responsibility. They are strategic level activities. Several shipyards make use of network-based computer methods to aid in the planning of production at this design stage where such factors as resource loading, method of payment and "experience" can guide decisions about milestones and approaches to outfit plans. Typically, these major milestones reflect strategic decisions about overall resource loading on the yard. Several shipyards are involved in the design and marketing of their own ships, hence potentially gaining significantly in production costs savings through repetition and the "learning curve" effect in production.

1.1.2.2 Production Planning

These activities are distinguished from milestone planning activities in that the conceptual planning done earlier in anticipation of contract can now be detailed and pushed into production after contract by means of production planning. These activities are categorized as tactical level activities. Once detailed drawings of the design are developed, these activities focus on breaking the production work down into tasks and grouping these tasks into work packages. The contents of the work packages are typically dictated by: 1) a scheduled total duration; and 2) a logical work method. After grouping and scheduling, the activities associated with monitoring and control for purposes of rescheduling include assessment of material and equipment availability, fabrication and assembly progress and outfitting progress.

A number of the shipyards utilized a planning concept in which groups were defined from the detailed drawings. These groups constituted work packages required to complete the production of a logically consistent subset of the ship. Groups become translated into man-hours of work and are used to determine the short interval schedules. These defined groups may also serve roles in cost accumulation and statusing. In nearly all shipyards contacted, explicit and primary concern in this scheduling endeavor was meeting the contracted deadlines or milestone points. These points are variously defined but generally include: start fabrication, lay keel, land and/or install major equipment, launch, sea trial and delivery. Since the detailed scheduling is by and large confined to these deadlines, a failure to meet the milestone deadline is treated as more important than completing the tasks in the group. Thus, tasks involved with preoutfitting are moved to later erection stages or to outfitting when rescheduling to meet milestone deadlines is done.

The majority of shipyards indicated that "completion time/duration/ time on ways" were the principal performance measures for production planning. Explicit consideration of costs is apparently not done at this more detailed stage and other possible measures such as labor smoothing and per cent preoutfit were of only small importance.

Computer use in detailed scheduling ranged from none in one shipyard through to heavy reliance in other shipyards where detailed scheduling by group within milestones is achieved with their software support systems and facets of control such as purchasing and inventory management are also accomplished.

When planning for preoutfitting or outfitting tasks in the definition of groups, certain "dos," "don'ts" and "rules of thumb" appear to be in general use. Some items are considered as must preoutfit because they would be locked out or covered over at a later erection stage. Inner bottom piping is a good example of this. Some items must not be preoutfit because of the danger of damage or pilferage in some later erection stage. Also all fixtures within about eighteen inches of a cut line have their installation delayed until after the cut and weld are made. Finally, some items or pieces of items (e.g. desk pedestals, wiring and piping hangers, etc.) might be preoutfit but don't have to be. For these items, the recognized opportunity to invert large sections to allow down-hand welding or installation, as opposed to vertical or overhead, presents a potential economic benefit for preoutfitting but may increase the time before launch for the work to be accomplished.

1.1.2.3 Bottleneck Considerations

Most shipyards agree that they have bottlenecks and attempt to schedule around these problems. Only one shipyard contacted did not consider itself as having bottlenecks. Crane lifting capacity was most frequently listed as causing bottlenecks. Production practices (e.g. size of subassembly) interact with preoutfit practices (e.g. amount of piping, ductwork, electrical wiring) to generate the unit weights being lifted. Thus, given the present handling system, either more steel and less preoutfitting or more preoutfitting and less steel per design unit is the decision problem associated with the bottleneck.

The second major bottleneck mentioned by several shipyards is that of space at outfitting docks. They recognize that this problem arises due to deferred tasks from a preoutfit plan as well as material and equipment arrival delays.

Other bottlenecks noted include the number of ways and the area available for in-process storage of formed plate and subassemblies. No shipyard indicated that its shops (e.g. fabrication, piping, paint) created a yard bottleneck.

1.1.3 Summary

Current practice in the outfit planning decision problem appears to be that of heavy emphasis upon "experience" as a principal factor. The decisions are constrained by the milestone dates established in the pre-award stage and, as one representative puts it, outfitting is clearly a "successor function" in most shipyard planning.

Where possible, preoutfitting is performed and includes those items most difficult to install at later stages. Certain items are delayed for installation by explicit decision. In between these positions rests a great many tasks that could be assigned to a preoutfitting category as well as to outfitting. All surveyed yards indicated a desire to increase their preoutfitting and the usual rationale was one of cost savings to do so. It is not clear from the information collected that shipyards are willing to relax their constraints on intermediate milestones so as to increase duration at earlier stages and thus allow for more preoutfitting. Nearly all shipyards expressed a great deal of interest in the examination of this question and the development of a means to answer it.

1.2 GENERAL PROBLEM STATEMENT

Outfit planning and outfitting are one clearly definable aspect of the total problem of planning and executing the production of a ship. In order to understand how outfit planning and outfitting are distinct yet interacting components of the total process, a more complete description of the shipbuilding process is needed.

1.2.1 Shipbuilding Process

A conceptual model of shipbuilding can be developed by considering the material flows and primary production facilities. As shown in Figure 1.2, ship production occurs in three primary facilities with two major categories of supporting facilities plus outside vendors.

The steel shops represent facilities where the steel forming activities take place. This includes welding of stiffeners and bracing to large

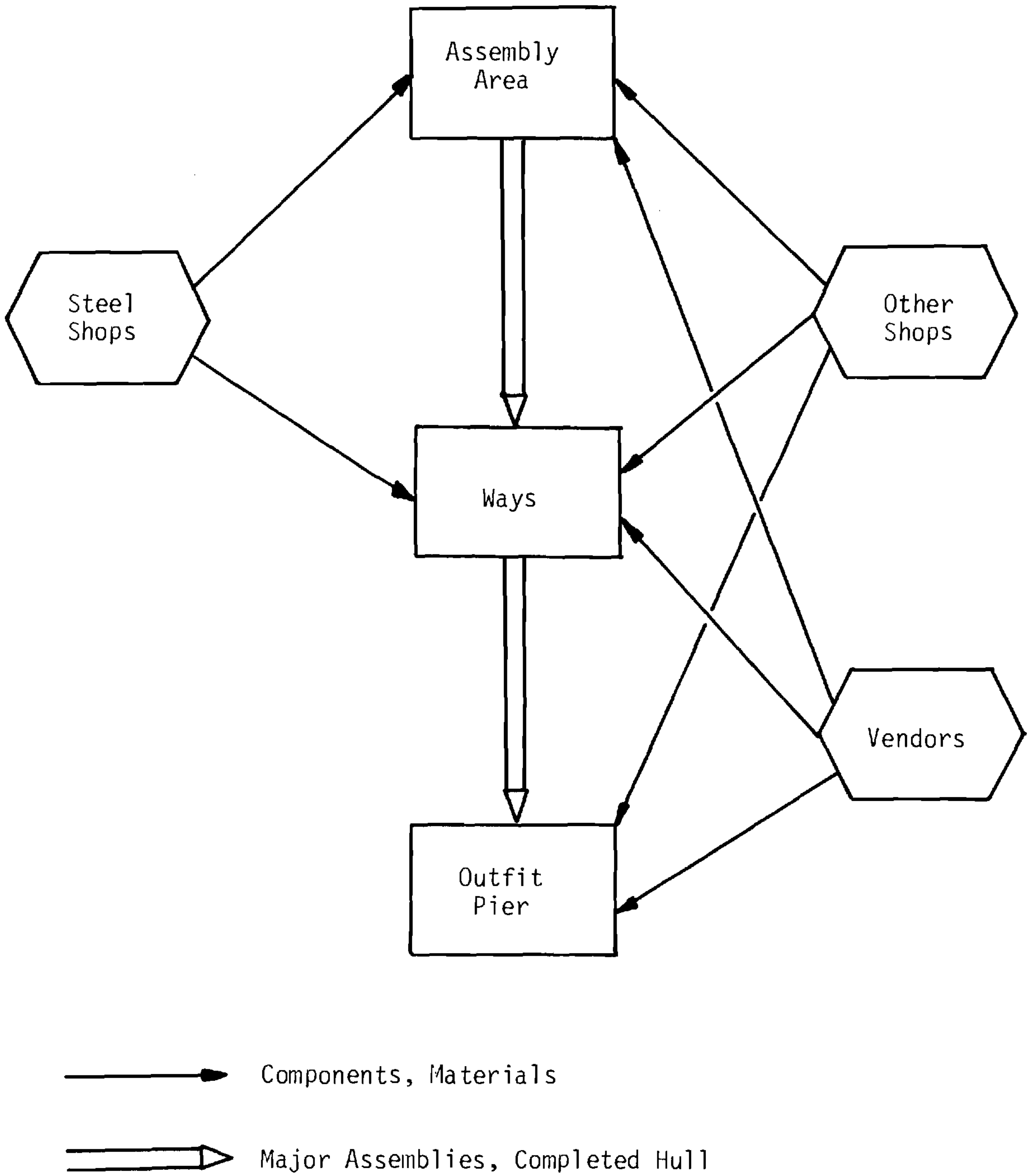


Figure 1.2 General Production Flow Model

steel plates. Similarly "other shops" include all the facilities associated with fabricating sheet metal, ducting, wire, piping, equipment, etc.

In this model, the "assembly area" represents any configuration of facilities where steel and/or other materials are brought together and processed prior to actual ship erection, i.e., prior to going on the ways. The ways area is the facility where ship erection, i.e., hull assembly, takes place. After hull assembly, the ship is completed at least to the point of being able to float. The "outfit pier" represents the stage of ship production which follows float-off.

The consideration of facilities and material flows leads naturally to the idea of different production <u>modes</u>:

(1) fabrication: the production of individual pieces of steel, sheet metal, ducting, piping, electrical cable, etc.

(2) assembly: fabricated plates are assembled to form <u>blocks</u>; also individual components may be assembled to form <u>units</u>, e.g., equipment with foundations, valves with piping, etc.

(3) erection: the activity on the ways that results in the completed hull.

(4) outfitting: the remaining production activities that take place once erection is completed.

Steel phase activities cannot be performed after erection, by definition. Outfitting phase activities, however, can be performed in any of the four modes. If they are done in a mode other than outfitting, then they are <u>preoutfit</u> activities.

Note that the terms "steel phase" and "outfitting phase" have been used to delineate activities by <u>type</u>. The four modes defined above, however, delineate activities by the timing of performance and facilities required. The distinction is an important one since there are options for many activities with regard to production mode.

A more specific description of outfitting is provided by the <u>zone outfitting</u> concept [7, 8]. Outfitting <u>on-board</u> corresponds to either erection (for the already completed portions) or outfitting modes as defined above and subsumes "preoutfitting" as currently practiced. Outfitting <u>on-block</u> corresponds to the assembly mode, and involves partial outfitting of blocks prior to their being lifted onto the ways. Outfitting <u>on-unit</u> also corresponds to the assembly mode, although it could occur geographically in a shop area.

This conceptual model of the shipbuilding process imposes no restrictions on the organization or scheduling of production activities. It also requires no assumptions about the organization of labor in the yard. The model must, however, include consideration of capacities and, by implication, schedules, since there are different projects, or ships, competing for access to the limited production capacity.

1.2.2 Outfit Planning Problem

When the production of a particular ship is being planned, necessary production activities are defined by some planning group (in practice, the level of planning detail at this stage varied tremendously). When this has been accomplished the production activities can be visualized as a large project network diagram, as in PERT or CPM [28, 33]. The exact configuration of this diagram, of course, depends on the particular yard's production technology as well as its planning capabilities.

In theory, then, production scheduling would take the large project networks for all the ships in the yard, and assign the various activities to the several facilities to be performed during a specific time period. For a variety of reasons, this is not a realistic approach and, naturally, is not used by any shipbuilder. The fundamental problem would be the tremendous overhead required to coordinate so many different activities associated with different ships.

In practice, the production process is somewhat "batch" oriented, in the following special sense. Even though production can be described as a large project network problem, each project will in general require dedicated use of the ways for some period of time. Thus, production control is greatly simplified by grouping together, or batching, the activities associated with a given ship at each production stage.

A natural approach to production planning in this setting is to schedule each ship by specifying the times during which it will have access to the three major production facilities. This approach lends itself readily to a Gantt chart description as illustrated in Figure 1.3. In fact, current practice in many shipyards is to schedule the major milestones for each ship, "start fabrication," "lay keel," "float-off," "builder's trials," and "delivery," and use these milestone event times as deadlines for the detailed production scheduling required at each production stage.

It is generally true however, that the milestone deadlines are based on a (single) given outfitting plan. If there are outfitting options for many different outfitting phase activities, the specified milestone deadlines may limit the number of options that can be selected.

On the other hand, there are some outfit phase activities which are always done in a specific preoutfit mode, e.g., inner bottom piping, and

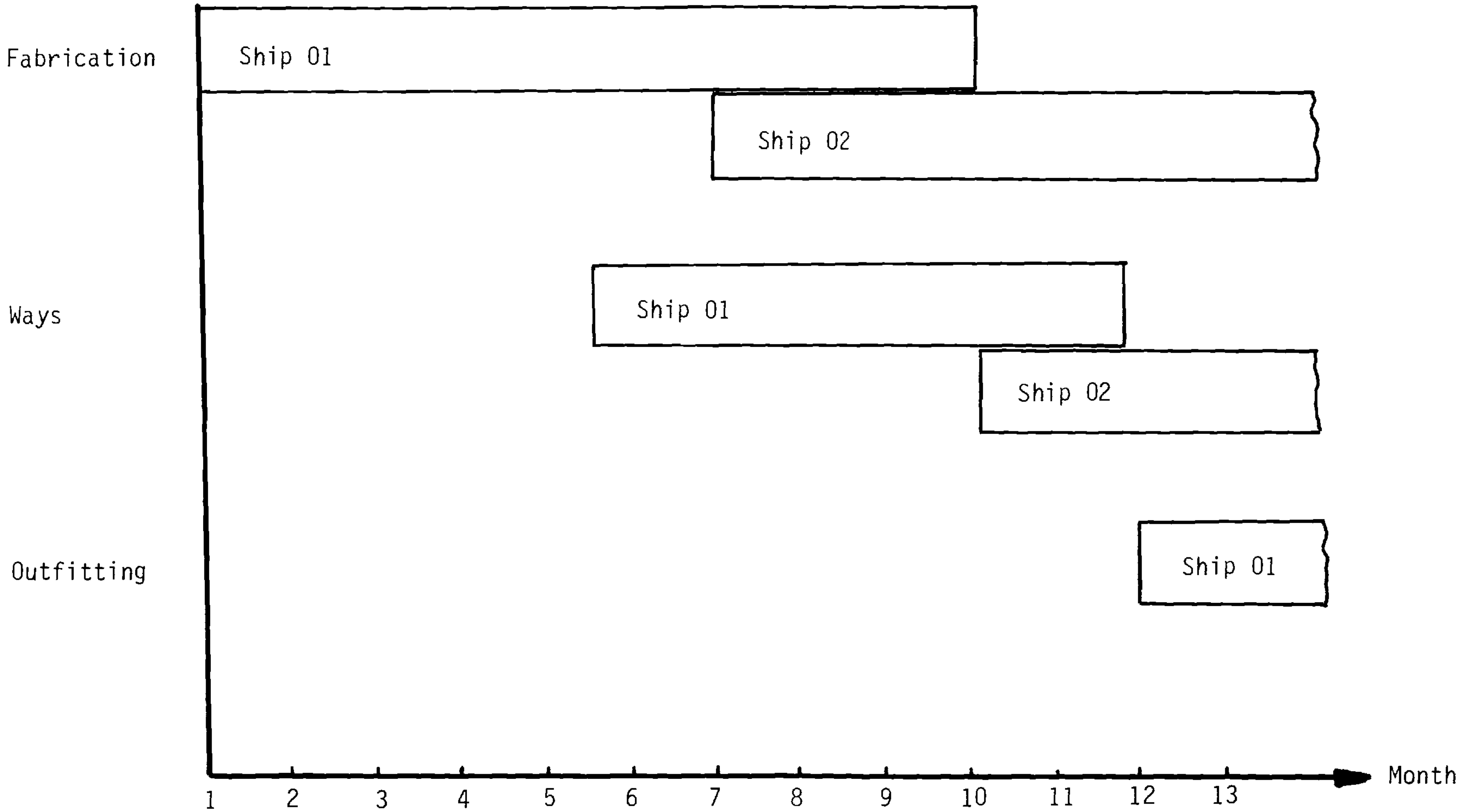


Figure 1.3 Hypothetical Gantt Chart

some that are never done in a preoutfit mode, e.g., electronic instruments. Since no outfitting options are required for these two types of outfit phase activities, they will not be considered further.

The <u>outfit planning problem</u> can now be stated more precisely as follows:

Given: (1) a catalog of the outfit phase activities for which there are outfitting options;

(2) for each such activity, a list of the outfitting options, including time, resource and precedence requirements;

(3) the ship delivery schedule and any fixed milestone deadlines;

(4) labor availability by craft and grade;

(5) facility capacities and availabilities (lifting, covered space, yard space, etc.); and

(6) other constraining factors (material availability, rate of cost accumulation, etc.).

Determine: The outfitting option to be used for each outfit phase activity considered, along with the necessary schedule.

The outfit planning problem is one of selecting from a number of interrelated options, a set of options that will satisfy the given resource constraints while optimizing some criterion, such as outfit costs or delivery date.

1.2.3 Issues in Outfit Planning

There are a multitude of issues to be considered in attempting to solve the outfit planning problem. Perhaps the single most critical issue is the design dependence of the solution. That is, the design of the ship and the design of the work breakdown structure define the limits within which outfit planning operates. More specifically, if no outfitting options are defined, then there is no outfit planning problem (or, alternatively, it has been solved implicitly by the production planner).

Especially in commercial shipbuilding, the negotiations between the builder and the owner may lead to terms that complicate or preclude preoutfitting. Examples are special requirements for coatings, construction methods, or standards. Very often, the impacts on outfit planning are not considered during the negotiations.

These issues, however, must be resolved outside the outfit planning process. Of more interest here are the issues that must be resolved within the outfit planning process. In particular, the issues of criteria, constraints, and other impacts must be considered.

The outfit planning problem, as defined in this research, deals only with the options available for outfit phase activities. By treating as exogeneous the deadlines, owner payments, labor management, etc., it is proper to consider the criterion as minimization of outfitting costs. Note that if the decision problem also included steel phase activities, milestone setting and payment terms, it might be proper to consider the criterion of minimizing total shipbuilding cost or maximizing profit.

In the outfit planning for a single ship, the constraints fall into two categories, absolute constraints and allocation constraints. Absolute constraints are those defining absolute capacity limits which are relevant for a single ship. Examples would be lifting capacity of cranes, maximum size or tonnage allowed on the ways, or technological constraints on ships.

Allocation constraints, on the other hand, result from allocating the yard's total resources to the several ships in process at any time. For example, the manpower available for a ship is a constraint, but it results from a decision allocating the total labor pool to the various ships in the yard.

The outfit plan must satisfy the following constraints:

(1) do not exceed the available lifting capacities (absolute)

(2) do not violate any milestone deadlines (allocation)

(3) do not exceed the labor availability in any craft or grade (allocation)

(4) do not exceed the available production or storage space (allocation)

(5) do not violate the given budget schedule (allocation).

A more general treatment of the problem would also consider the strategic level allocation of resources to the individual ships being produced. Such a treatment is beyond the scope of this research project.

Beyond the constrained resources, the outfit plan has a number of important impacts. In general, greater proportions of on-unit and on-board outfitting imply a long term trade-off between more highly skilled labor on one side and lower skilled labor and additional facilities on the other side. That is, with more such preoutfitting, there would be some shift from labor factors toward capital factors.

There is general agreement that the direct impacts on labor of outfitting on-unit and on-block are several. First there would be a reduction in hazard exposure because working conditions would be improved. (An indirect consequence would be a reduction in Workmen's Compensation expenses.) Second, the improved working conditions would result in improved quality. Third, as mentioned earlier, the possibility of substituting lower grade labor would reduce the labor cost if not the labor hours. All of these impacts would be manifested in improved labor productivity.

Increasing the amount of on-unit and on-block outfitting has a significant impact on the planning and supervision of production. In planning, the impact is a requirement for more detailed planning with construction drawings of sufficient detail available at the proper time. It also means that detailed scheduling may be required, even to the level of manpower loading by work order.

The impact on planning has both positive and negative components. On the positive side, the detailed scheduling should improve work flow and labor utilization and material acquisition. On the negative side is the obvious need for a management information system to support the planning and control functions at a very detailed level.

These "other effects" associated with the outfit planning problem must be evaluated separately in the decision of whether or not to attack the problem as described here. Because their effects are relatively difficult to quantify and because the associated costs would have to be amortized over all affected ships, they are not incorporated directly in the outfit planning problem.

1.2.4 Summary

The outfit planning problem arises from a need to resolve the various outfitting options associated with outfitting activities. It is concerned with minimizing outfitting costs subject to certain schedule and resource constraints. Outfit planning decisions have other impacts on facilities, labor and planning and control systems which are not treated as part of the outfit planning problem.

The problem as posed here is to determine which outfitting options to use and how to schedule the activities. It is concerned with economic rather than technological factors. It is specifically assumed that all relevant outfitting options for each activity have been defined and analyzed to determine their individual time and cost characteristics. This approach specifically does <u>not</u> address the problem of <u>determining</u> the individual activity outfitting options.

1.3 PROBLEM IMPORTANCE

Production levels for both merchant and naval vessel construction in United States yards have been fairly high over the past few years. This apparently was due to increased merchant activity following the Merchant Marine Act of 1970 and a continuing emphasis on the need to upgrade the U.S. Navy fleet. The anticipation however, is that this volume will significantly decrease for several yards, due to generally reduced orders worldwide and to increased competition from foreign yards for U.S. orders. The plan for FY 1979 for MarAd included $279 million for construction-differential subsidies. U.S. Navy funding for the same period for shipbuilding and conversion was to be $4.7 billion with an additional $2.9 billion for repair and alteration. These represent substantial amounts of money associated with the shipbuilding industry and thus improved productivity, though small on a percentage basis, can still result in substantial savings. One way to improve productivity appears to be increased levels of preoutfitting to gain cost reductions and possibly to gain reductions in schedules and delivery dates.

Such productivity gains may not come easily. A principal difficulty is the sheer complexity of many modern ships and the process associated with their production. The number of technical requirements in outfitting and the complexity of ship systems may not coincide with the ship size and so tonnage is not necessarily a good measure of outfitting volume or difficulty. Further, the number of drawings required and their degree of detail, coupled with the problems of timely delivery, are potential problem areas associated with the data base needed for good decisions in outfit planning.

Productivity gains are similarly difficult to achieve with high labor turnover and the resulting inexperience in the labor force. This is especially true where turnover compounds with a decentralized decision system placing heavy reliance upon first line managers for planning decisions as well as day to day implementation. Better production control would appear to result from centralized decision making under such circumstances and improved productivity should result from better planning decisions at that level.

Potential productivity gains in preoutfitting cannot be measured well at this time. It is possible to examine the cost of outfitting as a percentage of total production costs and thus estimate the dollar volume of shipyard outfitting nationally. A small percentage gain in outfitting productivity would then be translated into actual dollar amounts on a national scale and hence establish the problem importance in monetary terms. These dollar values are not readily released by the industry although one estimate for a complex naval vessel suggested that nearly 50% of the <ins>total</ins> labor costs is associated with outfitting.

A second way to look at problem importance involves the potential reduction in the total time between contract award and delivery. If increased preoutfitting can aid in achieving this reduction (see Literature Review Section) then more yard volume may be possible and yard capacity is increased. The improved competitive position due to cost and to delivery date may enhance a yard's ability to gain this increased volume even though national levels of shipbuilding activities appear to be decreasing.

2.0 LITERATURE REVIEW

As indicated earlier, the terms preoutfitting and outfitting do not appear to have standardized meanings in the shipbuilding industry and this is similarly reflected in the literature. According to Goldbach [20] preoutfitting is the "most common terminology currently applied to the installation of piping ventilation, electrical cables and machining prior to erection of structural assemblies." On the other hand, Andrews [2] terms outfit as "installation of piping, ventilation ducts, heads, electrical cable harness, ventilation machinery rooms, foundations and similar items" in the hull, no matter the status of the production activity.

According to Chirillo [6], the Hull Block Construction method is being used widely in the shipbuilding industry. Hull Block Construction employs zone-by-zone construction, which is construction on a geographically divided portion of a product such as the cargo hold, engine room and their subdivisions. Zone-by-zone construction employs an approach to outfitting, termed on-unit, on-block, on-board. Outfitting on-unit is the assembly of an interim product to be installed subsequently in the hull structure (see Figure 1.1). It is noted that as much as possible should be assembled "on-unit" in shop areas because progress of the hull structure is not delayed and overall safety and productivity are enhanced. Outfitting on-block is the installation of outfit components, or even a unit, into a hull structure assembly or block prior to its erection. Outfitting on-board, where on-unit and on-block is used, is limited to "1) the installation of electronics equipment and insulation that otherwise would be damaged by weather, 2) connecting the system interfaces between units and blocks, 3) applying a final paint coat, 4) and tests and trials." The term preoutfitting is also referenced in the literature as "pre-packaging" and installation of equipment, components and systems into modules [25, 37].

Planning for preoutfitting is usually done when detailed working drawings are available in the pre-keel period and are relatively free from design error or change. It is also facilitated when computer aided planning systems can be accessed [2, 20]. The computer aided planning of schedules for drawings, labor allocation planning and material requirements planning not only makes it easier to coordinate preoutfit with steel erection but also may improve overall control and coordination. Preoutfitting is also facilitated if a backlog of structural items is maintained [20].

It has been suggested that production lines should be organized to prefabricate items that will be installed in the preoutfitting stage [2]. Since these items must be transported to a specific location, labor and handling cost savings can be realized by locating these prefabrication areas adjacent to the preoutfit site.

Preoutfitting is reported in Europe in the Burmeister, Wain and Keller Howaldtswerke yards. These yards attempt to install as much machinery and preoutfit as much as possible in each subassembly prior to erection. The Japanese and Swedish shipyards build hull sections which are preoutfitted with desks, bulkheads, piping, ventilation, ladders and hatches. Prefabrication of assemblies begins two to three months prior to keel laying. Also, modular construction techniques developed successfully in some companies during World War II have been continued to the present in order to reduce production costs. An example of these efforts is the preoutfitting for hull sections of the AE32-35 at Ingalls [20] and the preoutfitted hull sections of tankers at SEATRAIN in New York [25].

There is a pattern in the literature that suggests preoutfitting is most applicable where the number of outfit tasks to be done is high, position or access aboard ship is poor and dimensional tolerances are not critical. This appears to be why preoutfitting is considered more applicable to complicated ships such as the FDL(X) ships, and less applicable for simpler bulk carriers and tankers. J. J. Henry [37] used the concept of preoutfitting repetitive tasks such as piping, ventilation, and electrical wiring in a standardized manner in the construction of modular deckhouses.

Some of the benefits cited for preoutfitting are increased productivity, reduced time between contract award and delivery [6], less lost material, less rigging and ease in testing because there are fewer other tasks to be performed at the test time. In companies where on-unit assembly is performed there are increased opportunities for improving safety and quality and achieving higher productivity levels because the "on-unit" assembly shops provide ideal climate, lighting and access. The uninterrupted construction and assembly in parallel create a more favorable environment with an associated increase in labor efficiency. Worker morale may also be improved, as in the case of the Ingall's yard. Morale was apparently improved by preoutfitting the hull modules, because the modules provided shelter from inclement weather.

Some negative aspects include possible layout and access complications, potential incompatibility of system interfaces, and additional costs, although which costs might increase was not reported.

Cost savings due to preoutfitting were often cited. The J. J. Henry report [37] concluded that preoutfitting of electrical, piping and ventilation systems was among the five largest potential areas of cost savings in what was called modular construction. Also, Goldbach [20] states that preoutfitting under appropriate conditions can make a significant contribution to cost savings and to schedule performance.

In summary, there is a lack of literature addressing the preoutfit problem. The few articles that discuss preoutfitting do so mainly when discussing modular construction. Very little material is available concerning the use of preoutfitting in the conventional construction process. In fact, preoutfitting was identified as a shipbuilding industry-wide problem area at the Shipbuilding Industrial/Production Engineering Workshop in February, 1978 [42]. The panel on Production, Planning, and Control recommended that preoutfitting should be explored in depth as a possible way to reduce costs in the industry. The existing literature does stress the fact that preoutfitting improves productivity, decreases costs, and may aid the reduction of time between contract award and delivery.

3.0 DEVELOPMENT OF MATHEMATICAL MODEL

To facilitate the development of the model, the outfit planning problem is restated in brief. Outfitting activities are those production activities associated with fabrication and/or installation of any material other than hull steel. Chirillo and Jonson [8] defines three stages for outfitting:

> "Outfitting on-units is the assembly of an interim product consisting of manufactured and purchased components . . . includes all but final paint coat. Units are composed exclusively of outfit materials and do not incorporate any hull structure.
>
> "Outfitting on-block is the installation of outfit components, perhaps units, onto a hull structural assembly or block prior to its erection."

Outfitting on-board, then, is the installation of outfitting materials in the erected hull structures, either prior to or following float-off.

This characterization of outfitting stages leads naturally to a similar characterization of the outfit components themselves. There are some outfit components which are only installed in the on-board stage e.g., furnishings and other similar materials which are subject to damage or pilferage are always installed in the on-board mode. These will be designated <u>on-board components</u>. Of the remaining components, some are associated with distributed systems, e.g., wireways, ventilation ducting, rather than distinct units, e.g., pumps, motors, valves, etc. These will be referred to as <u>non-unit components</u>, since outfitting on-unit is not appropriate. Finally, there are the outfit components which can be identified by or associated with a specific unit. These will be referred to as <u>free components</u>, since any stage may be selected.

Note that these designations are fixed to some extent by design practices. For example, a given system consisting of, say, a pump and piping, may be conceived and designed in several ways. If it is treated simply as a collection of separate components which must be installed in the ship, then the components will have the "non-unit" designation. Alternatively, if the components are viewed as integral parts of a single unit or set of units, then they will have the "free" designation. Chirillo and Jonson [8] give examples of outfit components that may be associated with units, although they typically are not in U.S. shipyards.

Although a free outfit component can be associated with a specific unit, it need not be installed in the on-unit stage. The component may instead be installed on-block or even on-board. Non-unit components may be installed either on-block or on-board, but not, of course, on-unit. As indicated in the outfitting stage definitions, units may be installed either on-block or on-board. These relationships are summarized in Figure 3.1 where a three-way distinction is made between the component type, its production stage, and the production location.

Outfit planning requires, for each outfit component, a selection of outfit stage. The selection decisions are constrained by a number of factors. In particular, it is common practice to take the hull block erection schedule as fixed when planning the outfit activities. For example, each hull block has a fixed deadline for its completion, and at that point in time it is lifted onto the ways for erection. Thus, all on-block outfitting planned for that hull block must be completed before its erection date. Similarly, if a unit is to be installed in the block, all the associated on-unit outfitting must be completed in time to allow the unit to be moved into the block and installed before its erection date. Furthermore, if the block "closes in" any previously erected blocks, any large components (main engine, diesel generators, etc.) must be landed in these blocks prior to

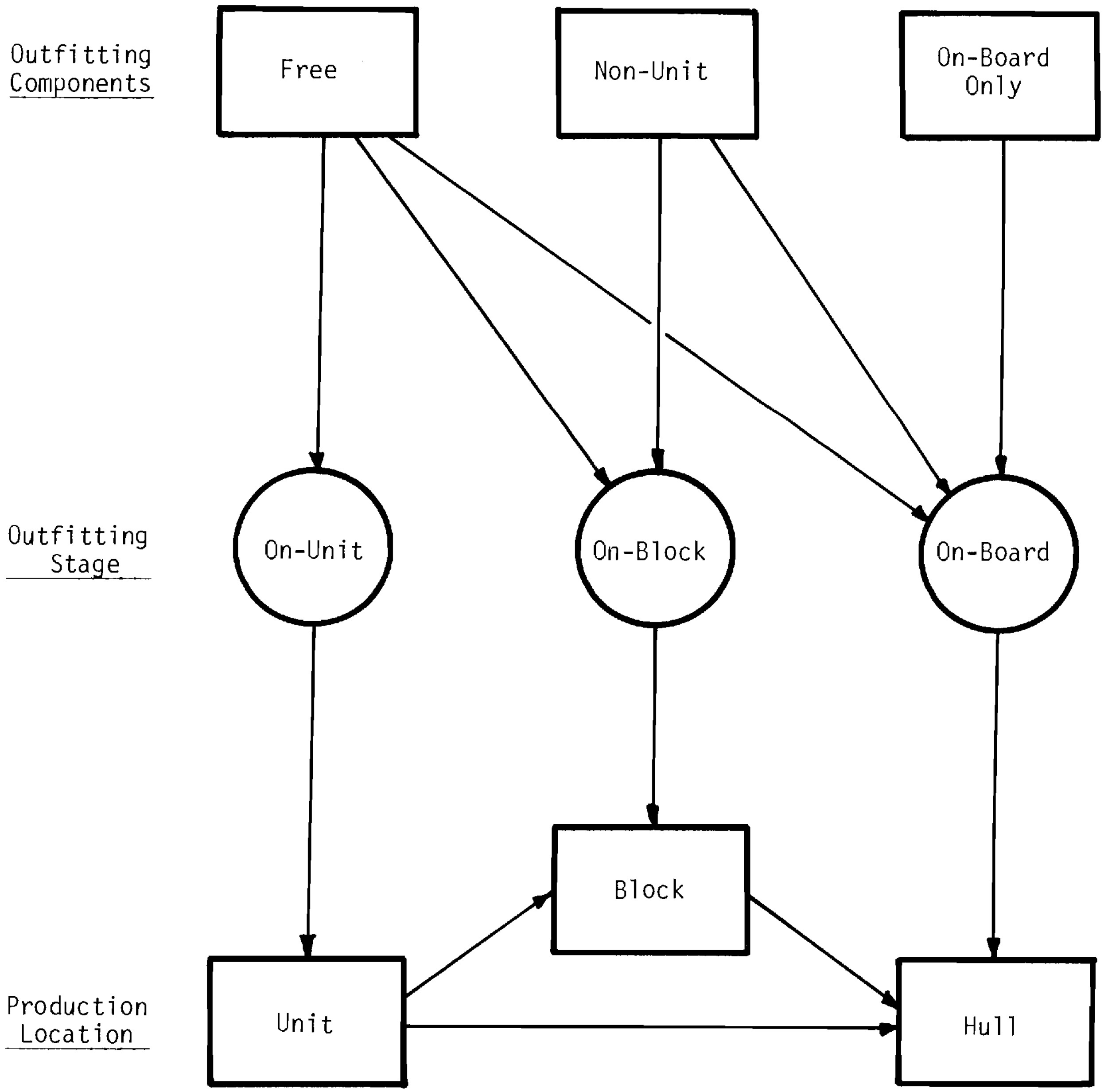


Figure 3.1 Relationships Between Outfit Components, Production Stages and Production Location

closing in.

The hull block erection schedule is a constraint in outfit planning because of convention. It is also conceptually possible to treat the hull block erection schedule as part of the decision process, i.e., if it were justifiable, a hull block might be delayed to allow more on-block outfitting to be performed. This practice does not appear to be in use currently in the U.S., and is not considered in the developments to follow. It is, however, common in Japanese shipyards, and may be adopted by U.S. yards in the future.

Another constraint which may affect outfit planning decisions in many yards is the available lifting capacity. Outfit units and outfitted hull blocks must not exceed the safe lifting capacity of the available equipment. Size is a similar consideration, i.e., units must be sized in light of the available access.

The effect of outfit planning decisions on limited yard resources must also be considered. Among the resources to be considered are labor and material availability and production or storage space. When determining outfit stages, care is required to insure that the resulting production schedule does not call for more labor than is available in each affected craft and grade. Likewise, since production typically requires space and fabricated components or units may need to be stored temporarily, the available yard facilities must not be overcommitted.

These resource allocation considerations are perhaps the most difficult aspect of outfit planning, especially in situations where multiple ships are in production simultaneously. The reason is that in order to guarantee feasibility of the mode selections, a feasible schedule must be determined. The selection decisions and subsequent scheduling decisions interact in a complex fashion and cannot be made independently.

So far, there has been no discussion of the specific criteria by which the outfit plan is to be evaluated. Several criteria may be considered, all motivated by economic considerations. As indicated previously, considerable cost savings are indicated [6, 8] for outfitting on-unit and on-block, relative to outfitting on-board. These cost savings result from lower skill requirements, better material access, less congestion, better quality control, etc. Thus one criterion, which should be minimized, is total cost of outfitting.

Another result of increased on-unit and on-block outfitting would be reduced delivery time. Reducing delivery time is favorable to both owner and builder, since the owner has use of his ship sooner and the builder receives final payment sooner. In addition, the owner benefits from the reduced ". . . interest costs for the substantial accumulating investment represented by construction progress and for achieving maximum utilization of expensive facilities such as a building dock" [8]. Thus a second criterion, to be minimized, would be completion time.

In particular circumstances, other criteria might be applicable. For example, the particular pattern of contracts awarded to a yard may dictate expanding or contracting the labor force. These changes in the labor force could be eased by scheduling more or less "early outfitting," i.e., on-unit and on-block. Because this type of consideration is situation dependent, the developments to follow will be based only on the criteria of cost and completion time.

3.1 MODEL FORMULATION

The outfit planning problem requires the specification of certain work elements and the determination of their associated production schedule. The problem has many similarities to general project scheduling problems and this appears to be a good way to approach the formulation of an appropriate conceptual and mathematical model.

3.1.1 Activity Networks in Ship Production

Ship production is essentially "one off," that is, ships are produced one at a time, rather than continuously as are, for example, automobiles. There is not much opportunity (nor economic justification) to mass produce ship components or to build ships on assembly lines. Thus, a natural approach to modelling ship production involves the use of activity network models such as CPM or PERT [28, 29, 30, 31, 33]. For practical as well as academic reasons (see, e.g. [13, 23]), only deterministic, i.e., CPM-like, models will be considered.

The use of <u>d</u>eterministic <u>a</u>ctivity <u>n</u>etworks, or DANs [15], to model ship production requires some assumptions about the ship building process.

A1: Ship specifications, such as production drawings, can be converted into well defined, distinct work packages, or <u>activities</u>.

A2: Assuming unlimited production resources, the only relationship between the activities is one of sequence or <u>precedence</u>. An activity, "A," precedes another activity, "B," if "A" must be completed before "B" can be initiated.

These two assumptions permit graphical representation of the relationship between production activities. There are several different such representations - the one used in this research is the <u>a</u>ctivity <u>o</u>n <u>n</u>ode, or AON, representation [15] and is illustrated in Figure 3.2.

Note that assumption A2 does <u>not</u> limit the relationships between activities to precedence only. Other types of relationships are possible, for example, two activities may require the use of the same limited

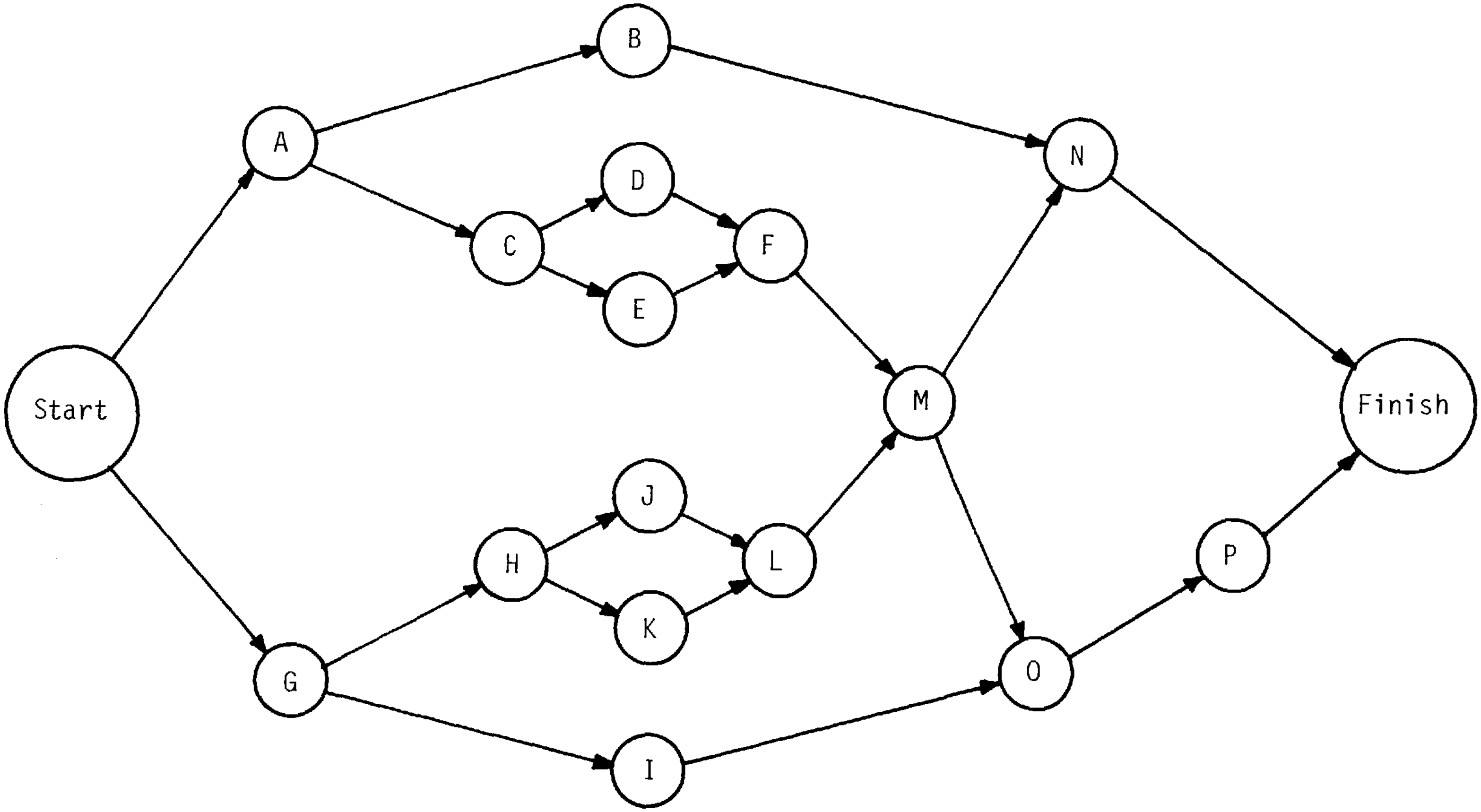


Figure 3.2 Sample Activity Network

resource.

A3: Associated with each activity is information about its duration (including resource-time options), about its requirements for various resources, and about its due date (or completion deadline) if appropriate.

In order to use the DAN model in planning, it must include certain information about the activities or work packages beyond precedence relationships. At a minimum, each activity has a given duration and resource consumption. In addition, it is often the case that the activity duration depends on the rate at which resources are applied, i.e., there are resource-duration options. For example, two men may complete a painting job in 4 days, where 4 men could complete the job in 2.5 days. Start and due dates are often imposed because of special considerations beyond just the work content of the project, e.g., a hull erection schedule.

A4: The various resources required to perform the activities are explicitly defined and the availability of the resources over the planning horizon is specified.

The resources required by the activities can be of two types. Some resources are consumed as they are applied to production, e.g., steel which is applied to a particular hull block. Any subcontracted material falls into this category. This type of resource must be available when the associated activity is scheduled.

The other resource type is available at a certain rate rather than a total amount. For example, a given labor pool in a particular craft translates into a fixed number of man hours per day of that resource. No matter how those manhours are allocated today, the same number of man hours will be available tomorrow. Of course, over the long run, the number of man hours can be changed by changing the size of the labor pool. Thus, this type of resource is not "used up" in the same way that materials are.

Resources of this type present more difficult planning problems for the following reasons. The cost of the resource depends on the rate at which it is available rather than the rate at which it is used, i.e., if the resource is not fully utilized in some period, there is a wasted resource cost. Thus, one goal is to schedule the productive activities so that resources of this type are always fully utilized. When there are several projects competing for the same resources it should be relatively easy to meet the goal of full utilization. Paradoxically, it is much more difficult to allocate the resources to the projects in order to optimize other, additional criteria.

Once the DAN model is constructed, it may be analyzed in several ways to assist in activity scheduling. The classical "early start" and "late start" times [4, 15, 36] can be calculated for each activity, allowing identification of the "critical path" and "critical path activities," i.e., activities which cannot be delayed without delaying ship delivery. Resource levelling techniques [10, 12, 32] can be used to determine a schedule which "smooths" out the resource requirement profile. If there are absolute limits on resources, then resource constrained scheduling techniques [5, 11, 30, 49] may be used to find a feasible activity schedule. Analytic techniques are also available for optimizing the resource-duration trade-off decisions [10, 15, 16].

The classical DAN models, such as CPM, are inadequate for the outfitting planning problem because they are based on the assumption of a single, unambiguous definition of the activities. In contrast, the essence of the outfit planning problem is to select a particular activity definition (i.e., select production modes) from among all the available alternatives. It will be necessary to extend the DAN models to incorporate this additional complexity and to develop the corresponding extensions to the analytic methodologies.

3.1.2 An Activity Network Model of the Outfit Planning Problem

The goal of the following discussion is the development of a conceptual model for the outfit planning problem which is consistent with the activity network based approach to planning and scheduling described in the previous section. It must be recognized at the outset that the process being modelled exists only hypothetically and that the model does not represent any existing process. It is apparently the case that, at the present time, very few U.S. shipyards employ any activity network based planning or scheduling procedures; thus, the proposed model constitutes a significant departure from currently standard practice. On the other hand, it is also apparently true that interest in this type of methodology is growing in many U.S. shipyards, so that the proposed model is in line with longer term trends in the industry.

3.1.2.1 Defining the Activities

As indicated earlier, classical DAN models do not allow alternative methods for accomplishing work elements. The incorporation of this feature will be the major point of departure for the model of the outfit planning problem. For this reason, it is of primary importance to specify the nature of the alternative activity definitions.

Current practice in U.S. production planning ([1], appendix 4) calls for work packages of 200-2000 man-hours, involving a <u>single</u> craft or trade. For comparison, the Japanese practice [8] is to define work packages of 40-120 man-hours. The following developments are based on the premise that activity descriptions can be made at the level of the smallest fabricated component and then aggregated as necessary. Furthermore, an activity, as discussed in the previous section, may consume several different resources, i.e., it may involve two or more crafts. The organizational and operational ramifications of this departure from standard practice will be explored later.

In developing the model, it will be useful to maintain the distinction between outfit <u>components</u>, which are associated with the outfit materials, and the outfit <u>activities</u>, which are associated with production, i.e., fabrication, assembly and installation. The outfit components were categorized as on-board, non-unit, or free, and outfit activities were classified as on-unit, on-block or on-board. The question which follows from this classification scheme is, "How are the activities corresponding to a given outfit element defined?"

A fundamental assumption about outfit planning is the following:

A5: On-unit outfitting is preferred to on-block outfitting, which is preferred to on-board outfitting.

This assumption implies that if there were no resource conflicts, or time constraints, outfitting would always be done as early as possible in the production process. It is the resource conflicts and milestone event deadlines which lead to deviations from this "ideal" outfitting plan.

Free Outfit Components

The free outfit components present the greatest latitude in planning production since they may lead to on-unit, or on-block, or on-board production activities, or to a combination. As a consequence, these are the activities that present the most difficulties in formulating the DAN model of outfit planning.

The "ideal" outfitting plan would call for maximum use of the on-unit stage, with the resulting units being installed whenever possible. Thus, the following assumption is made:

> A6: The outfit planning process creates for the free outfit components, a catalog of maximally outfitted units. For each unit, all the required materials, fabricated pieces and assembly work elements are specified. The set of outfit work elements for a given unit will be referred to as the <u>maximum outfit set</u> for the unit.

A particular unit from this catalog will generate many individual activities in the model (recall that the individual activities may be aggregated at a later step in the planning process). For example, each individual component of the unit must be either fabricated or purchased, resulting in the definition of either a fabrication activity or a purchasing activity. Each subassembly operation likewise results in the definition of a distinct activity.

An implicit requirement is that the units in this catalog are non-overlapping. In other words, no free outfit component is a component of more than one unit. Thus, the definitions of the units themselves is considered as fixed, the result, perhaps, of an earlier stage in the planning process. The problem of selecting from among alternative unit definitions can be included in the proposed model only in certain fairly restrictive situations. This point will be addressed in greater detail later in the study.

It may be the case that selection of the on-unit outfitting rather than on-block or on-board "induces" additional work elements. For example, additional bracing may be required to prevent damaging the unit during handling and moving. Any such induced work must be reflected in additional activities in the DAN model.

Since the ideal outfitting plan may not be feasible given the available resources and milestone event deadlines, it is necessary to specify the alternatives to be allowed within the outfit planning model.

A7: For each unit, there is a set of outfit components which represents the least amount of on-unit outfitting that can be done and still be economically justifiable. The associated set of outfit work elements will be called the minimum outfitting set for the unit.

This assumption implies that if a particular unit is selected from the catalog for on-unit outfitting, it need not be completely outfitted. However, it will include at least those outfit work elements contained in its minimum outfitting set. Associated with the maximum and minimum outfit sets are related sets of outfit components, designated as the maximum and minimum outfit kits.

A given unit may be fabricated in the on-unit mode. If so, it must include all components in its minimum outfit kit and it may include any additional components in its maximum outfit kit. Any work elements from the maximum outfit set which are not selected for on-unit outfitting must be performed at a subsequent stage, i.e., either on-block or on-board. The outfitted unit itself also may be installed on-block or on-board. If installed on-block, its assembly and installation must be completed before the block erection deadline.

These possibilities can be incorporated in a CPM-like precedence diagram as illustrated in Figure 3.3. In this example, nodes 1-4 represent the purchase, fabrication, or subcontracting activities for outfit components in the maximum outfitting kit for some unit. In other words, these are the activities which yield the outfit components themselves. The components corresponding to nodes 2, 3 and 4 are in the minimum outfitting kit for the unit, i.e., at least these components must be included if the unit is selected for fabrication.

A component, such as the one corresponding to node 1 in the figure, which is in the maximum outfitting kit has the following characteristic.

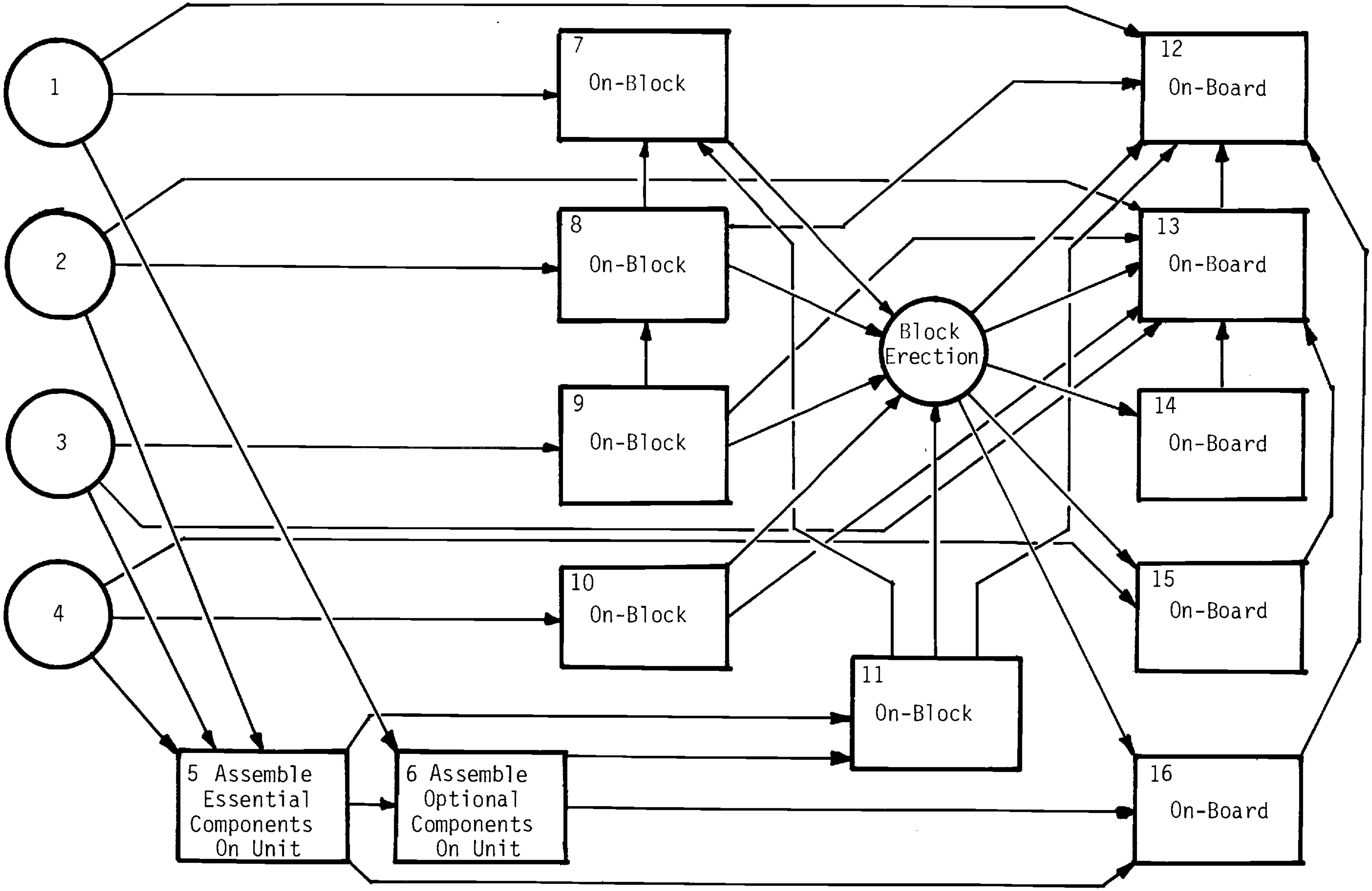


Figure 3.3 Activity Model for Free Outfit Components

It is a component which could be included in the unit fabrication and, in fact, it would be desirable to include it. However, if there are frustrating circumstances, for example, insufficient fabrication lead time or insufficient resources (labor, equipment, or material), then such a component may be left off the unit. It is, in a sense, an auxiliary component of the unit. On the other hand, components in the minimum outfitting kit are considered essential to the unit, so much so that they cannot be omitted from the unit.

The activities represented in the diagram by square nodes are the ones subject to the outfit planning decisions, which designate the specific stage of outfitting for each component.

To insure that components produced by the first four activities in Figure 3.3 are actually installed, the outfit planning decisions must obey the following guidelines:

(1) Exactly one activity is selected from each of the sets:
{6,7,12} to insure that element/component 1 is included;
{5,8,13} to insure that element/component 2 is included;
{5,9,14} to insure that elemnt/component 3 is included;
{5,10,15} to insure that element/component 4 is included;
If activity 5 is selected, activities 8, 9, 10, 13, 14, and 15 cannot be selected.

(2) Activity 6 can be selected only if activity 5 is selected;

(3) If activity 5 is selected, then either 11 or 16 must be selected; if 5 is not selected, neither 11 nor 16 can be.

If these three guidelines are followed, then a feasible solution will be constructed for the outfit planning problem. Note that if an activity is not selected, it simply becomes a discarded option, i.e., it does not affect subsequent scheduling or resource allocation decisions.

The example illustrates additional details that can be incorporated in this type of model. For example, if in addition to the minimum outfitting kit, component 1 is also to be included in the on-unit outfitting (i.e., activity 6 is selected) the associated work element, activity 6, must be completed by the time the unit is installed, either on-block (activity 11) or on-board (activity 16). This is indicated by the precedence relationships (5, 6), (6, 11) and (6, 16).

In this example, there is a required sequence for installing the outfit components; component 2 cannot be installed until after components 3 and 4 have been installed, and component 1 cannot be installed until after component 2 has been installed. These requirements are satisfied by requiring that activity 13 has as its predecessors, either 9 or 14, and either 10 or 15. Similarly, activity 12 has as predecessors either 8 or 13. Note also that if activity 5 is selected (i.e., the unit is assembled) then on-block or on-board outfitting for component 1 must <u>follow</u> installation of the unit.

Finally, note that the block erection schedule can be introduced into the model simply by specifying a due date for the unnumbered node corresponding to block erection. One additional consideration was left out to simplify the figure and the discussion. It might be desirable to treat on-board outfitting as two distinct stages, one corresponding to pre-float off outfitting and one corresponding to wet-dock outfitting. This consideration could be affected within the model simply by defining four additional nodes, one for each of the four outfit components, and adding the necessary precedence relationships. This is illustrated for the previous example in Figure 3.4.

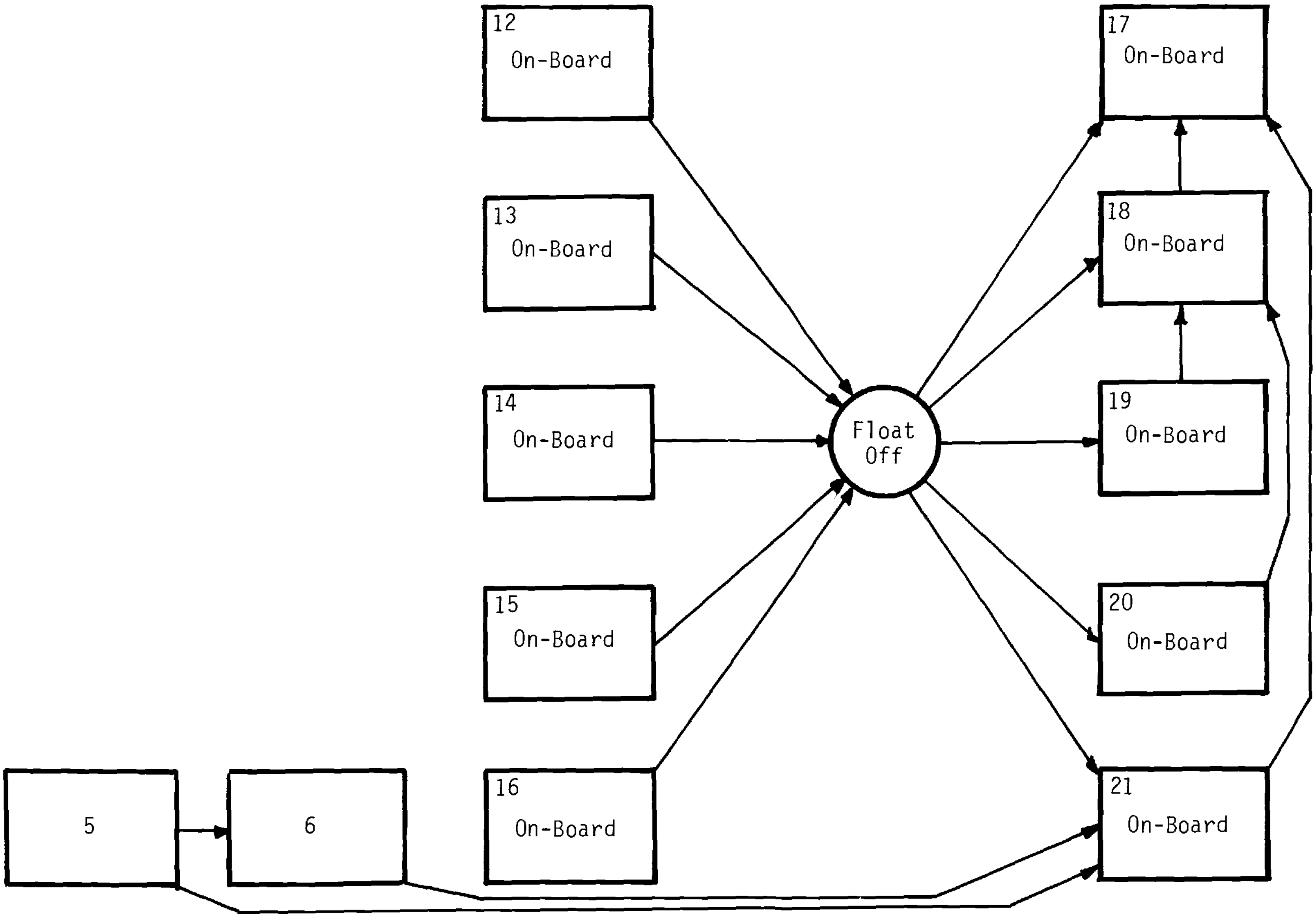


Figure 3.4 Adding Two Sub-Stages to the Model

Non-Unit Outfit Components

The non-unit outfit components involve fewer production options than the free outfit components and it is therefore considerably easier to define the alternative activities generated by them. In fact, non-unit components generate a subset of the activities generated by free components. For instance referring to the example of Figure 3.3, suppose the on-unit outfitting activities, which are activities 5, 6, 11, and 16, are omitted. The resulting activity network would describe the options available for non-unit components 1-4.

In addition to sequencing requirements among the non-unit components, there may also be sequencing requirements between the non-unit components and certain free components or their associated units. The various types of relationships are summarized in Figure 3.5. As indicated in the figure, the model must account for the possibility of sequencing requirements between the non-unit components and certain free components or their associated units, as well as between the non-unit component and certain on-board components.

As with the free outfit components, it is conceptually easy to extend the model to allow two distinct on-board outfit stages. The illustration will not be repeated.

On-Board Outfit Components

The on-board outfit components require no outfitting mode decision, unless the possibility of two on-board stages (pre-float off and wet-dock) are allowed. In this case, each component generates two alternative outfitting activities with precedence relationships as shown in Figure 3.6. The requirement, then, is to select exactly one of the two activities.

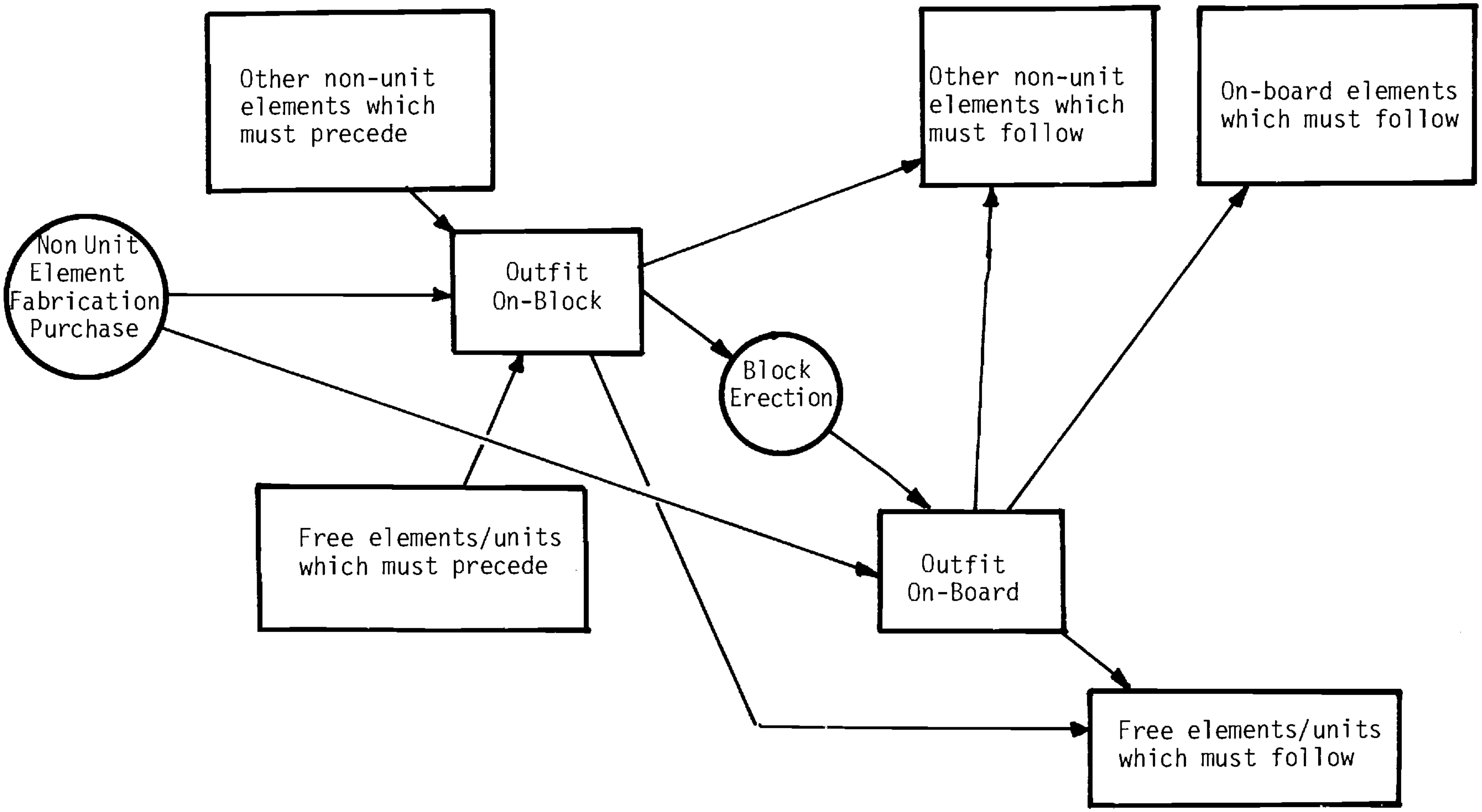


Figure 3.5 Activity Model for Non-Unit Components

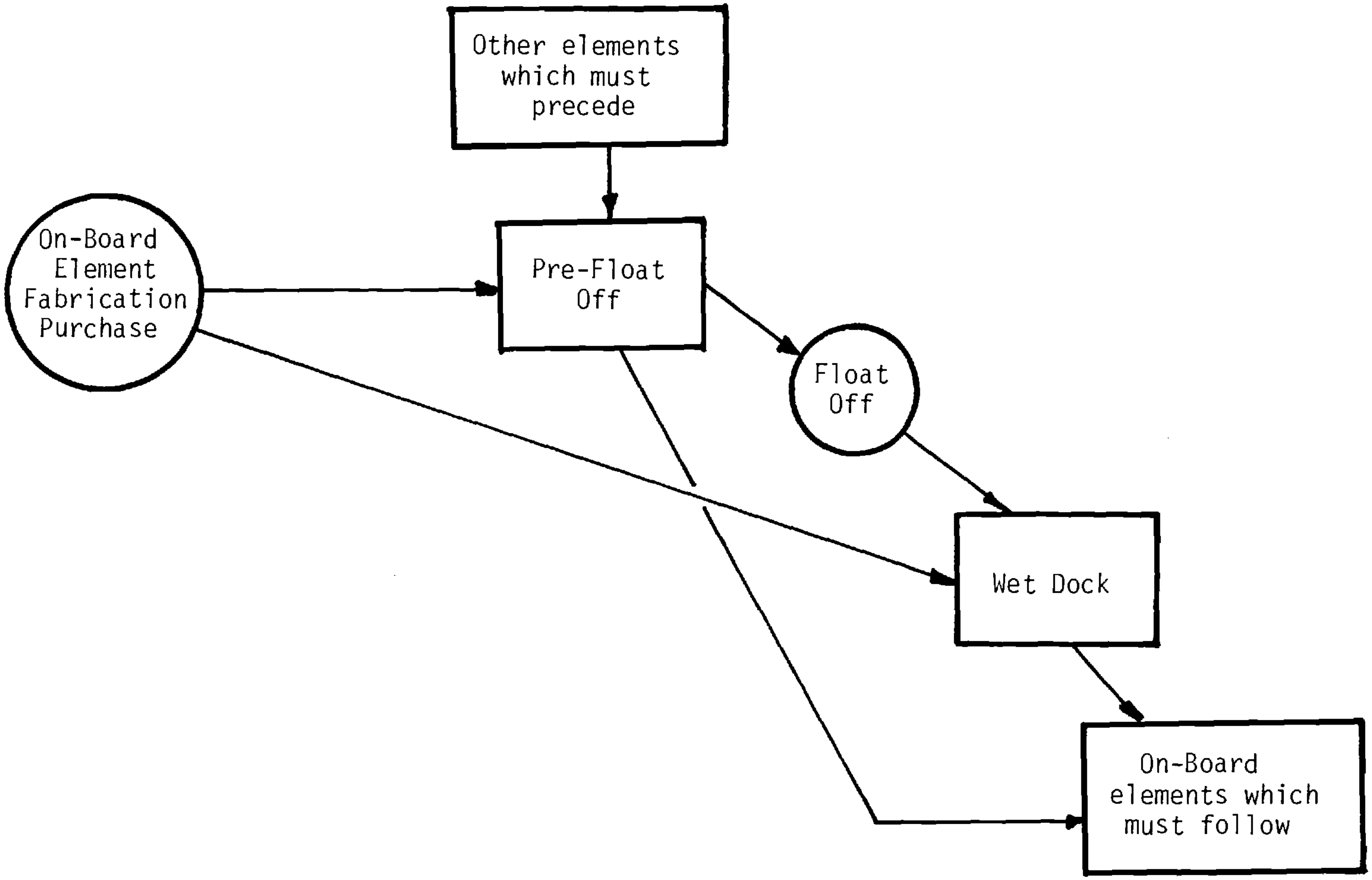


Figure 3.6 Activity Model for On-Board Components

3.1.2.2 Defining the Decisions and Constraints

The fundamental decision required in the outfit planning problem is the resolution of the options associated with each outfit component. This selection decision considers the activity network and requires a choice of exactly one of the alternative outfit activities for each outfit component (and perhaps the resulting unit). The selection decision must satisfy the sequencing requirements which are represented in the activity network as arrows. The sequencing requirements are constraints on the selection decision.

If there were no other constraints, the selection decision would be trivial because of assumption A5, i.e., each component would be outfitted as early as possible in the production process. There are, however three major types of constraints which may be violated by such a selection:

(1) [Time] The sequencing requirements may lead to a longer production time than is available from the given block erection and float-off milestones.

(2) [Labor] Even if there is sufficient time, the activities selected to be performed between two milestones may require more labor hours than are available in the crafts.

(3) [Weight and Size] Even if there is sufficient time and labor, the number of components selected for a unit or the number of units and components selected for a block may lead to a unit or block which is too large for the available facilities or access.

The constraints on time and weight may be easily checked once the selection decision is known. Such is not always the case, however, for the labor availability constraints.

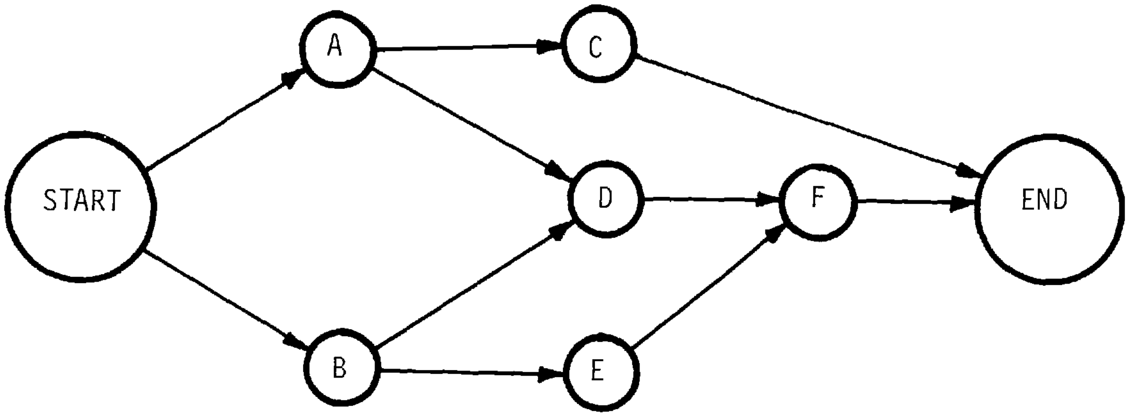
As mentioned earlier, labor resources have a somewhat unique nature. For example, it may not be easy to determine if an availability of 2000 man-hours during a five week period is sufficient to accomplish 1800 man-hours of work. Suppose that the available 2000 man-hours is the result of having a 10 man labor pool and that the 1800 man-hours of work required is described by the activity network shown in Figure 3.7. The resource profile for this activity network is shown in Figure 3.8, using the activity early start times from the CPM calculations.

It is obvious from Figure 3.8 that the 1800 man-hours of work cannot be accomplished using the available 2000 man-hours. The example further illustrates that in order to know whether or not a labor availability constraint is satisfied, a schedule for the activities must be specified. Thus, in situations where labor availability is a limiting factor, solving the outfit planning problem requires making a scheduling decision in addition to the selection decision.

The scheduling decision by itself is an extremely complex one. In fact, given the selection decision, the problem to be solved in making the scheduling decision is a "resource constrained CPM problem," [5, 11, 48, 49]. At the present time there is no optimization algorithm capable of solving large instances of this type of problem (see Bennington and McGinnis [5]) and based on recent results in combinatorics ([27], [43]) there is little hope that such an algorithm is possible. Thus, if solving the outfit planning problem requires a specific scheduling decision, any practical solution methodology will be heuristic in nature.

3.1.2.3 Defining the Criteria

The final step in formulating a model of the outfit planning problem



Activity	A	B	C	D	E	F
Duration	10	5	15	10	10	5
Resource Level	5	3	2	5	4	8

Figure 3.7 Sample Activity Network

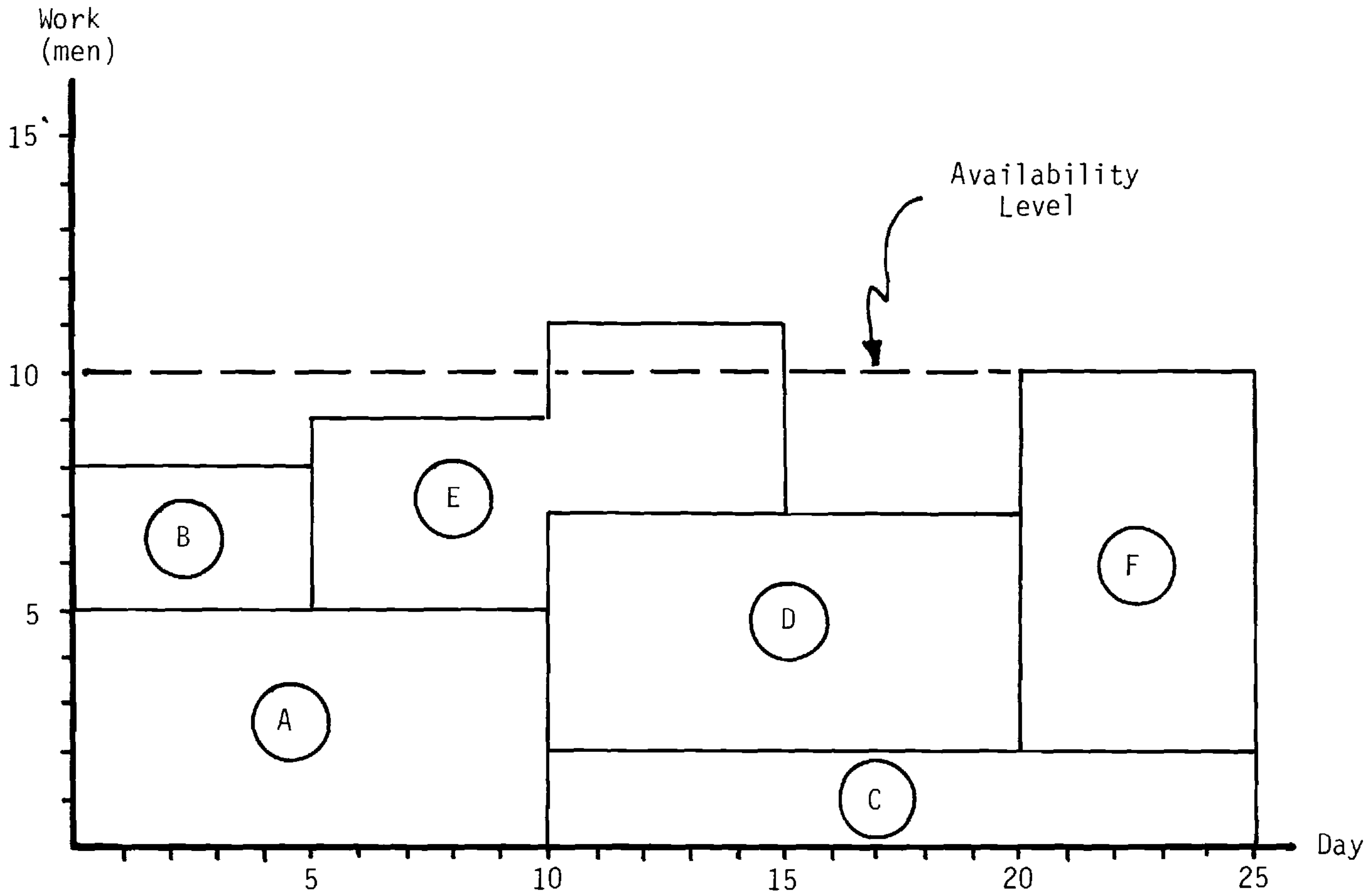


Figure 3.8 Resource Profile for Sample Network

is to define the criteria by which model solutions are to be evaluated. The problem of evaluation is complicated by the fact that there are two distinct kinds of decisions being made: outfitting stage selection and activity scheduling. Furthermore, a number of different viewpoints could be considered, each leading, possibly, to a difficult criterion.

The viewpoint adopted here is that the outfit planning problem is to be solved in the context of a number of prior, exogenous decisions which fix many of the outfit planning problem parameters. For example, the milestone event times (such as lay keel, float off, delivery, etc.) are assumed fixed, along with the detailed block fabrication and erection schedule. (Note, however, that the analytic framework could be used in deciding on the appropriate milestone schedule.) Resource availabilities are considered as exogenous factors.

Within the environment resulting from these exogenous factors, the goal in outfit planning is to minimize the cost of outfitting. Conceptually, then, all that is required is to estimate the outfitting cost associated with each of the outfitting alternatives. The best outfitting plan is the one with the smallest total cost. The goal of the scheduling component of outfit planning is to maximize labor utilization. This is accomplished when there are no periods in which the scheduled work content is less than the available labor.

While these two criteria are conceptually simple, their application may be difficult. In the first place, they require a significant effort in detailed estimation. The labor content, material and overhead costs, and duration must be estimated for each of several alternative outfit methods for a large number of outfit components. Current practice may not require such a detailed estimate for even one alternative. Clearly, procedures and methods will need to be developed for aggregating outfit components in the activity network and for semi-automating the estimation at the necessary level of detail. The information required for this estimation process will have to be accumulated over time as there is more experience with on-unit, on-block, and on-board outfitting.

A preliminary and crude approach to the first criterion is the following. Assume that the savings to be realized by outfitting earlier in the production process is a constant fraction of the total cost to outfit on-board. The fraction could vary with the type of outfitting (e.g., electrical vs. hydraulic systems), or with the total cost of the outfitting activity or some other factor. The criterion then becomes one of maximizing the total savings over outfitting completely on-board.

3.1.3 The Mathematical Model

In developing the conceptual model, two types of decisions were identified: selection decisions and scheduling decisions. It will be convenient to formalize the selection decisions first. Associate with each outfit component an index, i, where i = 1, 2, ..., N, N being the total number of outfit components. Similarly, associate with each outfit unit an index j = 1, ..., M, and with each block an index b = 1, ..., B.

The selection decisions will be represented by indicator variables. For a particular component, i, the variables are:

$$x_i^u = \begin{cases} 1 \text{ if component } i \text{ is outfit on-}\underline{\text{u}}\text{nit} \\ 0 \text{ otherwise} \end{cases}$$

$$x_i^b = \begin{cases} 1 \text{ if component } i \text{ is outfit on-}\underline{\text{b}}\text{lock} \\ 0 \text{ otherwise} \end{cases}$$

$$x_i^h = \begin{cases} 1 \text{ if component i is outfit on-board (in the } \underline{\text{h}}\text{ull)} \\ 0 \text{ otherwise} \end{cases}$$

Exactly one of the indicator variables must equal one for any component. However, not all stages can be selected for each element. Therefore, group the indices as follows:

F = set of indices of free outfit components

N = set of indices of non-unit outfit components

B = set of indices of on-board outfit components.

These sets are pairwise disjoint. Now the component selection decisions must satisfy:

$$x_i^u + x_i^b + x_i^h = 1 \qquad i \in F \tag{1}$$

$$x_i^b + x_i^h = 1 \qquad i \in N \tag{2}$$

$$x_i^h = 1 \qquad i \in B \tag{3}$$

Note that there is only one on-board option. The model can be readily extended to allow for pre-float off and wet-dock on-board outfitting. In order to simplify the exposition, this extension is not included.

There are similar indicator variables associated with each unit:

$$z_j = \begin{cases} 1 \text{ if unit j is selected for assembly} \\ 0 \text{ otherwise} \end{cases}$$

$$y_j^b = \begin{cases} 1 \text{ if unit j is installed on-block} \\ 0 \text{ otherwise} \end{cases}$$

$$y_j^h = \begin{cases} 1 \text{ if unit j is installed on-board} \\ 0 \text{ otherwise} \end{cases}$$

Since a unit cannot be installed unless it is first assembled, the unit selection variables must satisfy the following constraint:

$$y_j^b + y_j^h - z_j = 0 \qquad \forall\, j \tag{4}$$

The unit selection decisions and element selection decisions must be tied together. Define the following index sets:

L(j) = set of indices of components in the minimum outfitting kit for unit j

M(j) = set of indices of components in the maximum outfitting kit for unit j

The element and unit selection variables must satisfy:

$$\sum_{i \varepsilon L(j)} x_i^u - \|L(j)\|\, z_j = 0 \qquad \forall\, j \tag{5}$$

$$\sum_{i \varepsilon M(j)} x_i^u - \|M(j)\|\, z_j \leq 0 \qquad \forall\, j \tag{6}$$

where $\|S\|$ is the number of elements of the set S.
Constraint (5) requires that if unit j is selected ($z_j = 1$), then all the components in the minimum outfitting kit for that unit also must be selected. Constraint (6) permits additional components to be included in the unit only if the unit is fabricated.

The constraints (1)-(6) are <u>logical constraints</u> and merely guarantee consistency between the indicator variables and the decisions they represent. In addition, there are <u>structural constraints</u> which must be satisfied. One of these is the precedence relationships defined by sequencing requirements. Define

P(j) = index set of components (units) which must precede component (unit) j in production

Then the precedence constraints on the selection decisions are:

$$x_i^u + 2x_i^b + 3x_i^h - (x_j^u + 2x_j^b + 3x_j^h) \leq 0 \qquad i \in P(j) \tag{7}$$

$$y_j^b + 2y_j^h - (y_k^b + 2y_k^h) \leq 0 \qquad j \in P(k) \tag{8}$$

Constraints (7) and (8) require that for any component or unit, its predecessors must be outfitted or installed at the same or an earlier production stage.

A second category of structural constraints limits the total weight added to a unit or block. Note that these limits may be facility dependent, i.e., units fabricated in different shops may have different weight limits.

$$\sum_{i \in M(j)} w_i x_i^u \leq W_j \qquad \forall\ j \tag{9}$$

$$\sum_{j \in U(b)} \left(\sum_{i \in M(j)} w_i x_i^u \right) y_j^b + \sum_{i \in F(b) \cup N(b)} w_i x_i^b \leq W_b \qquad \forall\ b \tag{10}$$

where:

w_i = weight added by outfit element i

W_j = maximum weight allowed for unit j

U(b) = units which go into block b

N(b) = subset of components of N which go into block b

F(b) = subset of components of F which go into block b

W_b = maximum outfitting weight added to block b

The first term in constraint (10) is the total weight of units which are selected for installation on-block. The second term is the total weight of components (not part of a unit) which are outfitted on-block.

In order to deal with the time and labor availability constraints, the scheduling decisions must be formalized. Define the following scheduling variables:

t_i = scheduled start time for component i outfitting

θ_j = scheduled time for completing unit j fabrication

τ_j = scheduled start time for unit j installation.

The scheduling variables must satisfy all the precedence constraints as well as the scheduling limitations imposed by the steel schedule.

First, consider the constraints involving on-unit outfitting.

$$t_i x_i^u + d_i^u x_i^u - t_j x_j^u \le 0 \qquad i \in P(j) \tag{11}$$

where d_i^u = time to outfit component i on unit.

Constraint (11) requires that all predecessors of component j must be completed before component j can be outfitted on unit.

$$t_i x_i^u + d_i^u x_i^u - \theta_j z_j \le 0 \qquad \forall\ i \in M(j) \tag{12}$$

Constraint (12) requires all on-unit outfitting to be completed before the unit itself is completed.

$$\theta_j + d_j - \tau_j \le 0 \qquad \forall\ j \tag{13}$$

where d_j = material handling delay for unit j.

Constraint (13) is included to allow for possibly significant material handling delay or resource requirement.

The installation of units and outfit components on-block must not only satisfy precedence but "schedule window" constraints as well.

$$\tau_j y_i^b + d_j^b y_j^b - \tau_k y_k^b \leq 0 \qquad j \in P(k) \tag{14}$$

where d_j^b is the time required to install unit j on-block. Constraint (14) forces the on-block installation of unit k to be after the on-block installation of its predecessors.

$$\tau_j - T_b^s \geq 0 \qquad \forall\ j \in U(b) \tag{15}$$

where T_b^s = earliest possible time for on-block outfitting on block b. Constraint (15) forces the installation of the unit j to be after the time when installation is feasible.

$$\tau_j y_j^b + d_j^b y_j^b - T_b^f \leq 0 \qquad \forall\ j \in U(b) \tag{16}$$

where T_b^f = latest possible time to complete outfitting on block b. Constraint (16) sets the deadline for on-block installation of units.

There are similar precedence and schedule window constraints for the on-block outfitting of free and non-unit outfit components:

$$t_i x_i^b + d_i^b x_i^b - t_j x_j^b \leq 0 \qquad j \in P(i) \tag{17}$$

$$t_i x_i^b - T_b^s x_i^b \geq 0 \qquad i \in F(b) \cup N(b), \qquad \forall\ b \tag{18}$$

$$t_i x_i^b + d_i^b x_i^b - T_b^f \leq 0 \qquad i \in F(b) \cup N(b), \qquad \forall\ b \tag{19}$$

These same precedence and schedule window constraints are repeated for both units and elements for on-board outfitting. For the units, the constraints are:

$$\tau_j y_j^h + d_j^h y_j^h - \tau_k y_k^h \leq 0 \qquad j \varepsilon P(k) \tag{20}$$

$$\tau_j - T_h^s y_j^h \geq 0 \qquad \forall j \tag{21}$$

where T_h^s = earliest possible time for installing unit on-board.

$$\tau_j y_j^h + d_j^h y_j^h - T_h^f \leq 0 \qquad \forall j \tag{22}$$

where T_h^f = latest possible time for installing unit on-board.

For the outfit components, the corresponding constraints are:

$$t_i x_i^h + d_i^h x_i^h - t_j x_j^h \leq 0 \qquad j \varepsilon P(i) \tag{23}$$

$$t_i x_i^h - T_h^s x_i^h \geq 0 \qquad \forall i \tag{24}$$

$$t_i x_i^h + d_i^h x_i^h - T_h^f \leq 0 \qquad \forall i \tag{25}$$

In addition to precedence and schedule window constraints, the scheduling decisions must be feasible with regard to the resource availabilities. Resource availability constraints are quite difficult to formulate in explicit terms, so the following approach is typically used (see, e.g., models in [5] and [10]). Define the following:

$A_e(t)$ = set of outfit components being outfitted at time t

$A_u(t)$ = set of outfit units being installed at time t

r_{icu} = level of resource category c required by component i when outfitted on-unit

r_{icb} = level of resource category c required by component i when outfitted on-block

r_{ich} = level of resource category c required by component i when outfitted on-board

r_{jcf} = level of resource category c required to fabricate unit j

r_{jcb} = level of resource category c required to install unit j on-block

r_{jch} = level of resource category c required to install unit j on-board

R_{ct} = level of resource category c available at time t.

Now the resource availability constraints are:

$$\sum_{i \varepsilon A_e(t)} (r_{icu}x_i^u + r_{icb}x_i^b + r_{ich}x_i^h) +$$

$$\sum_{j \varepsilon A_u(t)} (r_{jcf}z_j + r_{jch}y_j^b + r_{jch}y_j^h) \leq R_{ct} \qquad (26)$$

The difficulty with using such a constraint is that the sets $A_e(t)$ and $A_u(t)$ depend on the scheduling decisions. In fact this is, to a certain degree, the nub of the resource constrained project scheduling problem.

The constraints (1)-(26) can be shown to be redundant. For example, if the scheduling related precedence constraints, (11)-(25), are satisfied, then the selection related precedence constraints, (7) and (8), must necessarily be satisfied. The reason for including the redundant constraints, (7) and (8), is to allow for solution procedures which try to decouple the selection and scheduling decisions.

Since the criterion specified for the outfit planning problem is to minimize outfitting costs, define:

C_{iu} = cost of outfitting element i on-unit

C_{ib} = cost of outfitting element i on-block

C_{ih} = cost of outfitting element i on-board

C_{jb} = cost to install unit j on-block

C_{jh} = cost to install unit j on-board

The objective function for the mathematical model is:

$$\text{Minimize} \quad \sum_i [C_{iu}x_i^u + C_{ib}x_i^b + C_{ih}x_i^h]$$

$$+ \sum_j [C_{jb}y_j^b + C_{jh}y_j^h]$$

3.2 MODEL EVALUATION

A mathematical model has been developed to describe the outfit planning problem. This model is in the form of a mixed integer programming problem and, consequently, it presents formidable difficulties in solution. In fact, recent theoretical developments [27] have been interpreted as indicating that such problems (referred to as "NP-complete") cannot be solved optimally. Certainly it is true that, currently, practical problems of this ilk are not optimized. There are, however, a number of heuristic solution procedures which have been developed and used successfully to solve similar problems (e.g., see [36]).

Obviously, the model by itself cannot lead to better outfit planning. What is required is a systematic implementation of the model. There are several requirements for a successful implementation of the model, and these can be more easily discussed by referencing the diagram of Figure 3.9.

One of the requirements for a successful implementation is an appropriate methodology for solving the selection and scheduling problem for given milestone events and resource availabilities. As was indicated earlier, there is little hope for a general optimizing method for solving this problem, so in the most general case, the solution procedure will be

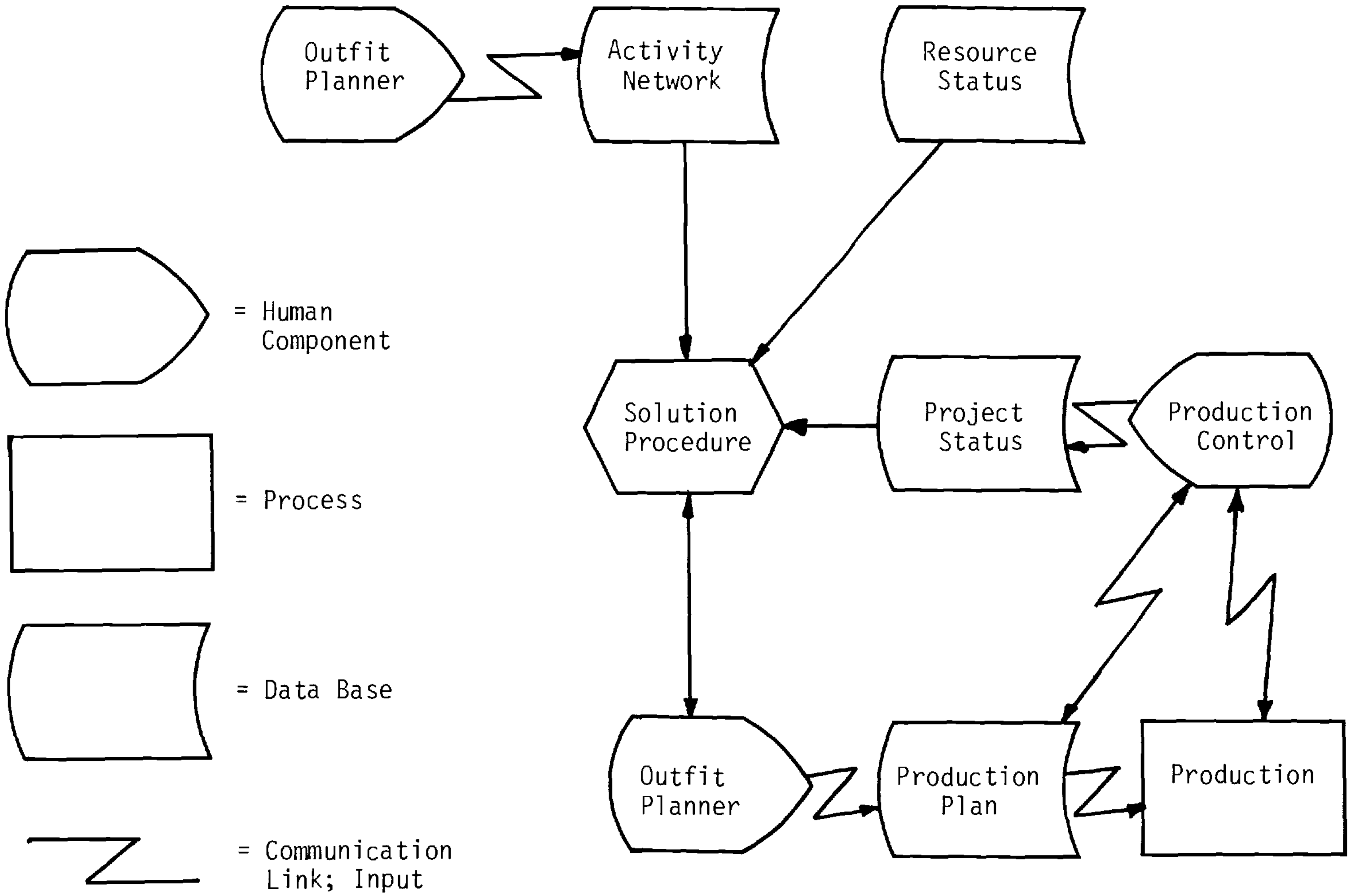


Figure 3.9 Outfit Planning Process

heuristic. The solution procedure does not currently exist - its development is the focus of Phase II of this research project, and is discussed further in the following sections.

The model requires large amounts of information and generates large numbers of detailed decisions. Thus, any practical implementation will require a fairly detailed, production oriented data base to support the solution procedure. Although many shipyards do not have such a data base at the current time, the SPARDIS system used by NASSCO [44] is one example of the type of system that would be required.

A third requirement is that the outfit planning process could in fact provide all the information required in the model. It appears that a major shift from current practice would be the idea of allowing (and therefore planning for) several alternative ways to accomplish the outfitting tasks. In addition, the use of the on-unit, on-block, on-board approach to outfitting is not currently widespread, although it is being strongly supported as a means for improving productivity [8].

Given that the on-unit, on-block, on-board approach has been adopted, defining the alternative outfit activities discussed earlier should be straightforward, albeit somewhat time-consuming. Observe that to a large degree, the outfit elements are associated with particular blocks. Therefore, the activity network resembles a large number of small subnetworks (one for each block) which are loosely connected by milestone events. It will be possible to "decompose" the network definition into smaller, more manageable tasks.

Figure 3.9 also indicates how the model might be used in practice. The use of the model for planning the outfitting of a ship is self-evident. Probably as important is the use of the model to "replan" when there are major deviations from the original plan. Such deviations might arise from bad estimating, from an excessive number of change orders, from bad weather, from unexpected demands on resources or from unexpected fluctuations in labor or resource availability.

A final point of discussion is the benefit to be obtained by the use of the model. The foremost benefit of the model, per se, is tighter planning and control of outfitting, resulting in higher productivity (and thus lower costs). In project-type work, such as ship production, it is important to correctly estimate the labor content of the work and then plan the work so that labor resource utilization is maximized. As the example given earlier indicated, it is not always obvious, even in simple problems, how to accomplish this. The proposed model provides a systematic means for coping with and coordinating the vast number of relationships which simply cannot be handled by an unaided human planner.

A secondary benefit from the proposed model is that it complements and strengthens the implementation of the on-unit, on-block, on-board approach to outfitting. It provides a systematic framework for identifying opportunities for on-unit and on-block outfitting as well as for determining the technical and economic feasibility.

3.3 EVALUATION OF POTENTIAL SOLUTION APPROACHES

The outfit planning problem as formulated in the preceding sections has not been treated previously in the literature of industrial engineering, operations research or management science. Although problems of resource allocation and problems of activity scheduling are often described and solved, the problem of simultaneously selecting the activities and scheduling them in the presence of resource constraints apparently has not been examined. There are, however, some models in the literature that are related to the outfit planning problem, and they will be discussed below.

Since the problem has not been examined before, there is no available procedure which can be directly applied to solve the problem. Thus, the solution methodology will have to be developed. The following discussion is intended to indicate the existing results upon which that development can be based.

It should be noted at the outset that the outfit planning problem is an extremely hard problem to solve. In the first place, it is a discrete optimization problem since it requires "yes-no" decisions about certain activities. In general, discrete optimization problems are hard to solve (see, e.g. [27] or [43]) and for many, if not most, no optimizing procedure is capable of solving problems of realistic dimensions. Secondly, the outfit planning problem is a generalization of the well-known resource constrained project scheduling problem. As Bennington and McGinnis [5], noted in 1973, no optimization algorithm is available which will solve this problem when more than about fifty activities are present. Although some work has been done since then, e.g. Talbot and Patterson [48], Stinson, Davis and Khumawala [47], the earlier conclusion is still valid.

It seems clear, then, that there is little reason to expect that an optimization procedure can be developed to solve practical instances of the outfit planning problem. Thus, for the general problem, the discussion of potential solution approaches will be limited to heuristic methods. Only for certain special cases, e.g., when labor resources are not a limiting factor will it be reasonable to attempt optimizing procedures.

3.3.1 Some Special Cases

The following discussion identifies some of the simpler special cases of the general outfit planning problem. For each case, the relationship to existing work is discussed and potential solution procedures are outlined.

3.3.1.1 No Resource or Lifting Capacity Constraints

The simplest special case is based on the assumption that there are neither resource nor lifting capacity constraints. In this case the only factor affecting outfit planning is the time available for on-block outfitting. This special case strongly resembles the so-called "project coordinator's problem," or PCP, treated by McGinnis and Nuttle [35]. There are, however, major differences between the two problems.

In the PCP, there is a single "deadline" for the completion of all selected activities, while in the outfit planning problem, there are "windows" during which certain activities must be performed, if they are selected. Also, the PCP permits only precedence and corequisite relationships between the activities (activities are corequisite if selecting one implies the other must be selected). The outfit planning problem, however, has more complicated relationships among activities.

Since each outfit component must be installed in some outfit mode, exactly one outfit activity must be selected for each component. This leads to what McGinnis and Nuttle [35] refer to as "mutual exclusivity" (at most one activity selected from a set) and "mutual inclusivity" (at least one activity selected from a set). McGinnis and Nuttle indicate that the presence of either type of relationships vastly complicates their problem, and, in fact, it is no longer solvable by their method. Thus, even in this simplest special case, there is no currently available optimizing procedure.

In the absence of resource constraints, the decisions required for each block are independent. Thus, any optimizing procedure for this special case should exploit the fact that the problem decomposes by blocks, i.e., the outfitting associated with each block can be considered independently of all other blocks. The effect of this decomposition is to reduce a single very large discrete optimization problem to a set of smaller, hopefully manageable problems.

Unfortunately, these smaller problems cannot be partitioned as is the PCP in the McGinnis and Nuttle procedure. The reason in the outfit planning problem, is that the selection decisions have an effect on scheduling; therefore, scheduling cannot be determined independently. Research will be required to discover whether or not the McGinnis and Nuttle procedure can be adopted for this case.

3.3.1.2 Lifting Capacity Constraints but No Resource Constraints

In this special case, it is assumed that the outfitted weight or size of some units or blocks might exceed the safe lifting capacity of the available equipment. As for the previous special case, the absence of other resource constraints allows the problem to be decomposed by blocks. As before, however, the resulting problem for each block is one for which no solution procedure is currently available.

If the lifting capacity constraint applies only to the block itself, then it takes the form of the second budget constraint discussed by McGinnis and Nuttle [35]. Generalizing their observation, the selection problem for this special case resembles a knapsack problem [38] with precedence constraints and generalized upper bounds [39]. It is reasonable to expect that such a problem could be solved using Lagrangian relaxation [18, 19] in conjunction with fast algorithms for the knapsack problem [3, 38]. Even if this proves possible, there is still the problem of optimally coordinating the selection and scheduling decisions.

3.3.1.3 Some Observations

In both these special cases, the problem decomposes by hull block, yet the resulting smaller problems are still not in a form for which optimization procedures are readily available. An appealing heuristic in these situations is to further decompose the problem as follows. Consider each mode or production stage in order (i.e., on-unit first, then on-block, then on-board). At each stage, solve an associated PCP using the procedure of McGinnis and Nuttle [35]. Any activity not selected becomes a candidate for a later stage. The function to be optimized should reflect the savings associated with not delaying the outfitting.

This "stage myopic" approach to the outfit planning problem obviously yields only a heuristic solution, i.e., there is no guarantee of optimality. It does have one extremely desirable aspect, however; since it eliminates the complicating relationships, the procedures described by McGinnis and Nuttle can be applied directly. The approach would therefore be quite efficient from a computational point of view. Empirical studies will be required to determine the quality of the solutions obtained by such a heuristic method.

3.3.2 The General Case

In the general case of the outfit planning problem resource constraints are assumed binding, along with, possibly, lifting capacity and size limitations. The block decomposition discussed above is no longer valid, and as a result, the solution procedure must consider not only the interaction of selection and scheduling within a block but across blocks as well.

As pointed out earlier, there are no readily available solution procedures which can be directly applied to the general problem. However, based on the existing literature, three potential heuristic approaches have been identified. Further research will be needed to determine which of these approaches holds more promise for solving practical instances of the outfit planning problem.

3.3.2.1 Resource Constrained Project Scheduling Approach

The literature on the Resource Constrained Project Scheduling Problem, or RCPSP, reveals no practical success with optimizing algorithms (see, e.g., the surveys by Bennington and McGinnis [5] or Davis [11]). Furthermore, the successful heuristic approaches all have the same basic structure, differing only in the implementation of one particular step. Thus, one approach to the outfit planning problem is to generalize this basic heuristic approach.

The basic heuristic approach to solving RCPSP can be summarized as follows:

(0) set $t = 0$

(1) let $S(t)$ be the set of all activities whose predecessors have all been completed by time t i.e., the activities $S(t)$ may be scheduled to start at time t. Let $\underline{a}(t)$ be the vector of remaining uncommitted resources. If $S(t) = \phi$, STOP.

(2) Using rule [R], select a subset of $S(t)$, call it $\hat{S}(t)$, such that every activity in $\hat{S}(t)$ can be scheduled to start at time t and the required resources will not exceed $\underline{a}(t)$.

(3) For each activity in $\hat{S}(t)$, let its start time be t. Determine τ to be the earliest completion time for any activity in process or scheduled to start at time t.

(4) Set $t \leftarrow \tau$; go to (1).

A number of rules, [R] have been proposed, but none of them is best for all problems. Davis [11] summarizes the work up to 1972 and, more recently, Cooper [9] has evaluated a set of 26 different rules.

This basic heuristic can be generalized quite easily for the outfit planning problem by permitting the scheduling and selection decisions to be made simultaneously. As an activity is selected in step (2) to be scheduled, all its alternatives are dropped from the network. Obviously, the key in this approach to devising an effective heuristic is the specification of the rule [R]. In particular, it is desirable to choose the "most valuable" subset $\hat{S}(t)$ which still "fits" within $\underline{a}(t)$. If a "value" can be associated with each activity in S(t), then, conceptually, rule [R] involves solving a multi-dimensional knapsack problem.

3.3.2.2 Selection-Scheduling Partitioning Approach

An alternative to the above simultaneous approach is to iterate between solving a selection problem and a scheduling problem. In this approach the selection problem attempts to maximize the value associated with the selection decisions. Given the selection decisions, the scheduling problem attempts to find a feasible schedule. If no feasible schedule can be found, the "values" must be adjusted in some manner and the selection problem resolved.

In this approach, the key element is the adjustment of the values, i.e., the coordinating mechanism linking the two decisions. Since the approach is iterative, it would seem to require more computational effort than the RCPSP based approach. On the other hand, since it allows adjustments, it would seem also to have greater capacity for finding good solutions to the problem.

This approach has one other potential advantage relative to the RCPSP based heuristic. The heuristics for solving RCPSP typically do not consider the trade-off between activity duration and the level of resources committed. The partitioning approach, however, could admit any reasonable scheduling procedure, in particular, one which explicitly allowed for such trade-offs.

3.3.2.3 Block Decomposition Approach

The resource constraints tie the decisions for different blocks together, preventing the type of block decomposition which was discussed for the special cases. One way to overcome this difficulty is simply to allocate the available resources (e.g., labor) to each block in each production stage. Within this allocation, the selection and scheduling decisions would attempt to maximize resource utilization. As for the partitioning approach, some coordinating mechanism would be required to allow the allocations to be adjusted if necessary. Thus, the decomposition approach would also be iterative.

The decomposition approach has some of the same desirable aspects as the partitioning approach. It is iterative and therefore should have a better chance of yielding good solutions. Conceptually, there is no reason to exclude the duration-resource level trade-offs in this approach. In addition, the decomposition results in smaller, more manageable selection and scheduling problems. It is conceivable that an optimizing procedure could be developed for these smaller problems, in which case, this approach would appear to be more promising than the other two.

3.3.3 Discussion

The outfit planning problem is a difficult problem to solve, and, moreover, has not been previously addressed in the literature. Even for some very simple special cases, no solution procedure is available. Promising approaches have been identified for the special cases and for the general problem. In some instances, the approach is related to, or a generalization of existing procedures, although this is not so for all. In the absence of empirical evaluation, little can be said about the effectiveness of the proposed solution procedures.

4.0 DESIGN OF TESTING PROCEDURE

The decision support system is intended to aid shipyard production planners in the planning for and scheduling of outfitting tasks and materials. Both the planning and the scheduling must be emphasized for each represents an important use of the system. Initial systematic planning of ship production at the strategic shipyard loading phase must necessarily include outfitting resources as these are significant elements of the complete process. Similarly, the capability to assess and re-assess schedules for outfitting with consideration of work progress, labor availability, lifting capacity and other changing resource constraints as well as bad weather delays is important in a tactical sense. Each type of use requires significant information and, with a system model based upon a Deterministic Activity Network formulation, will require computer resources.

The purpose of the testing outlined in the following discussion is to establish the validity of the conceptual approach to outfit planning. The fundamental method for doing so involves experimental computer software and a simulated outfit planning environment. More specifically, the focus of testing is on the solution procedure (yet to be developed) and the type of results obtained from the procedure. At this time, the supportive computer-oriented resources, such as large-scale data base management systems, are not to be evaluated.

4.1 BENCHMARK PROBLEMS

Thorough testing of the system under development is necessary both for a system validation purpose and for a demonstration purpose. Since completely serving both purposes may consume excessive resources from a limited budget, it is necessary to set priorities. Accordingly, the validation assumes a first priority and demonstration activities a second priority. It is to be noted that these are not mutually exclusive purposes and that this is reflected in the following material.

System validation requires that the computer implementation be tested so as to provide confidence that it presents logical solutions to the problem addressed. The problems addressed are to be of reasonable size and reflect the expected applications. Further, the problems should be of such a nature as to adequately exercise capabilities of the methodology imbedded in the code and the model. System validation can therefore be accomplished by use of hypothetical ship production data. Such data need not be accurate (in the sense of the real world of shipbuilders), but the computer code must deliver results consistent with the data supplied to it.

Considering the demonstration purpose that the system testing could serve, several options oriented around making the hypothetical data more reflective of the real world have been pursued. These range from using actual ship production data, suitably masked, from a cooperating U.S. shipyard to exploring the collective experience of selected shipyard production planners at certain points in the test process. Requests for collaboration were made to numerous U.S. shipyards with a general description of the information needs and the confidentiality protection provided (see Appendix).

In view of the testing priorities, the lead times for developing or collecting the testing data and the results of the requests for collaboration, the hypothetical ship production data will be developed for the validation testing. To the extent that individuals agree to share their judgements in the form of responses to direct questions, these data and testing approaches will be modified to point toward servicing the demonstration purposes noted earlier.

4.2 CRITERIA FOR EVALUATING TEST RESULTS

Shipyards consider the minimization of outfitting costs and the minimization of total production completion time important goals of production planning activities. The Advisory Committee reported the outfit cost criterion as paramount to an outfit planning function in the current context of shipyard organization. The total production completion time and total production cost criteria extended beyond outfit planning to include other organizational responsibilities.

The use of hypothetical ship production data means that comparison of test results with actual outfit costs of production will not be possible. The absence of this specific point of comparison, namely the results of currently utilized systems to achieve outfit plans, diffuses the nature of a specific performance standard for the model. The problem of evaluating benchmark problem test results from hypothetical input data is therefore more complex, in the sense of being less reducible to an overall measure, and must necessarily rely upon the analyst's assessment of the proper conclusions drawn by the model from the information supplied to it. The testing effort must therefore concentrate upon exploring the ranges of model parameters and reporting the results fully.

5.0 CONCLUSIONS AND RECOMMENDATIONS

A significant portion of the planning and construction of ships is associated with outfit materials, and as a result, outfitting is a major component of production costs. As this report demonstrates, the outfit planning problem can be conceptualized as a problem of selecting and scheduling activities in a deterministic activity network.

Formalizing this conceptual model leads to a very difficult optimization problem, and recourse to heuristic solution methods is required. Because of the magnitude of the problem and the complexity of potential solution procedures, any practical implementation will require the use of computer facilities. This requirement is further strengthened by the quantity of data used in the model and the number of detailed results produced.

The major result of this research effort has been the development of a formal mathematical model of the outfit planning problem, and the identification of several promising approaches for developing solution procedures. In addition, a program has been outlined for experimental evaluation of the model.

The next step in the research is to develop one or more of the possible solution procedures to the point where they can be implemented in computer codes. At that point, a suitable benchmark problem should be used to exercise the model in a variety of ways for formal evaluation. This evaluation should indicate whether or not it is appropriate to pursue a production-level implementation.

REFERENCE

1. _A Manual on Planning and Production Control for Shipyard Use_, Bath Iron Works, Bath, Maine.

2. Andrews, V. Benjamin, et al., "Conceptual Design of a Mechanized Shipyard for Fast Deployment Logistics (X) Production," National Technical Information Service, U.S. Department of Commerce, AD-752-595, December, 1965, pp. 1-88.

3. Balas, Egon, and Eitan Zemel, "Solving Large Zero-One Knapsack Problems," Management Sciences Research Report No. 408(R), Graduate School of Industrial Administration, Carnegie-Mellon University, Pittsburgh, PA, 1977.

4. Battersby, Albert, _Network Analysis for Planning and Scheduling_, St. Martin's Press, New York, 1970.

5. Bennington, G. E., and L. F. McGinnis, "A Critique of Project Planning with Constrained Resources," _Proceedings of the Symposium on Scheduling Theory and Its Applications_, S. E. Elmaghraby, ed., Springer-Verlag, 1973.

6. Chirillo, L. D., presentation to Chesapeake Section, SNAME, May, 1979.

7. Chirillo, L. D., private correspondence, Todd Pacific Shipyards Corporation, Seattle Division, January, 1979.

8. Chirillo, L. D., and C. S. Jonson, _Outfit Planning Manual_, National Shipbuilding Research Program, Project SP-IV-D, 1979.

9. Cooper, D. F., "Heuristics for Scheduling Resource-Constrained Projects: An Experimental Investigation," _Management Science_, Vol. 22, No. 11, 1976.

10. Davis, Edward W., "Resource Allocation in Project Network Models - A Survey," _Journal of Industrial Engineering_, April, 1966.

11. Davis, E. W., "Project Scheduling under Resource Constraints - Historical Review and Categorization of Procedures," _AIIE Transactions_, Vol. 5, No. 4, 1973.

12. Dewitte, L., "Manpower Levelling of PERT Networks," _Data Processing for Science/Engineering_, Vol. 2, No. 2, 1964.

13. Elmaghraby, S. E., "On the Expected Duration of PERT Type Networks," _Management Science_, Vol. 13, No. 5, 1967.

14. Elmaghraby, S. E., _Some Network Models in Management Science_, Springer-Verlag, 1970.

15. Elmaghraby, S. E., Activity Networks: Project Planning and Control by Network Models, Wiley, 1977.

16. Fulkerson, D. R., "A Network Flow Computation for Project Cost Curves," Management Science, Vol. 7, No. 2, 1961.

17. Garvey, John J., "The National Shipbuilding Research Program 1971-1976," presented to the Philadelphia Section Society of Naval Architects and Marine Engineers, April, 1976.

18. Geoffrion, A. M., "Lagrangian Relaxation for Integer Programming," Mathematical Programming Study 2: Approaches to Integer Programming, 1975.

19. Geoffrion, A., and R. McBride, "Lagrangian Relaxation Applied to Capacitated Facility Location Problems," AIIE Transactions, Vol. 10, No. 1, 1978.

20. Goldbach, Richard A., "Application of Preoutfitting During Construction of Ammunition Ships AE 32-35," Marine Technology, January, 1973.

21. Graves, R. G., L. F. McGinnis, and L. D. Bailey, "The Outfit Planning Problem," Department of Commerce Contract No. DO-A01-78-00-3074, June 15, 1979.

22. Gross, Donald and Pinkus, Charles E., "Optimal Allocation of Ships to Yards for Regular Overhauls," Technical Memorandum, Serial TM-63095, Office of Naval Research, Project NR 347-020, May, 1972.

23. Grubbs, F. E., "Attempts to Validate PERT Statistics or 'Picking on PERT,'" Operations Research, Vol. 10, No. 6, 1962, pp. 912-915.

24. Hurst, R., "Some Production Research Activities on Steelwork and Outfitting," The Society of Naval Architects and Marine Engineers, June, 1968.

25. Jolliff, James, V., CDR. USN, "Modular Ship Design Concepts, Naval Engineers Journal, Vol. 86, No. 5, October, 1974.

26. Johnson, C., "Scheduling Planning and Reporting Data Information Systems," National Steel and Shipbuilding Company, San Diego, Calif.

27. Karp, R., "On the Computational Complexity of Combinatorial Problems," Networks, Vol. 5, 1975.

28. Kelley, J. and M. Walker, "Critical-Path Planning and Scheduling,", Proceedings of the Eastern Joint Computer Conference, 1959.

29. Kelley, J. E., Jr., "Critical-Path Planning and Scheduling: Mathematical Basis," Operations Research, Vol. 9, pp. 296-320, 1961.

30. Kelley, J. E., "The Critical Path Method: Resources Planning and Scheduling," Industrial Scheduling, J. R. Math and G. L. Thompson, eds., Prentice Hall, 1963.

31. Levy, F. K., G. L. Thompson, and J. D. Wiest, "Mathematical Basis of the Critical Path Method," Industrial Scheduling, J. F. Muth and G. L. Thompson, eds., Prentice Hall, 1963.

32. Levy, F. K., G. L. Thompson, and J. D. Wiest, "Multi-Ship, Multi-Shop Workload Smoothing Program," Naval Research Logistics Quarterly, Vol. 9, No. 1, 1963.

33. Malcomb, D. G., J. H. Roseboom, C. E. Clark, and W. Fazar, "Application of a Technique for Research and Development Program Evaluation," Operations Research, Vol. 7, pp. 646-669, 1959.

34. McGinnis, L. F., and R. J. Graves, "A Mathematical Model for the Outfit Planning Problem," Department of Commerce Contract No. DO-A01-78-00-3074, October 31, 1979.

35. McGinnis, L. F., and H. L. W. Nuttle, "The Project Coordinator's Problem," OMEGA, Vol. 6, No. 4, 1978.

36. Moder, J. J., and C. R. Phillips, Project Management with CPM and PERT, Reinhold, 1964.

37. Modular Design Applications Study (Deckhouse and Outfit), The U.S. Department of Commerce Maritime Administration, Contract No. MA-4358, PB 178196, 1967, pp. 1-57.

38. Naus, R. M., "An Efficient Algorithm for the 0-1 Knapsack Problem," Management Science, Vol. 23, 1976.

39. Naus, R. M., "The 0-1 Knapsack Problem with Multiple Choice Constaints," University of Missouri-St. Louis, 1976.

40. Padberg, M., and T. Shaftel, "The Modular Design Problem: Convexity of the Constraint Set," Management Science Research Report No. 245, Carnegie-Millon University, March, 1971.

41. Potts, W. R., and W. L. Cuthbert, "L.N.G. Carriers Using the Conch Containment System," The Society of Naval Architects and Marine Engineers, No. 11A, 1975, pp. 21-40.

42. Proceedings for Shipbuilding Industrial/Production Engineering Workshop, R. J. Graves, ed., U.S. Department of Commerce, February, 1978.

43. Sahni, S., and E. Horowitz, "Combinatorial Problems: Reducibility and Approximation," Operations Research, Vol. 26, No. 5, 1978.

44. Scheduling Planning and Reporting Data Information System, National Steel & Shipbuilding Company, San Diego, California.

45. Shaftel, T. L., Thompson, G. L., "A Simplex-Like Algorithm for the Continuous Modular Design Problem," Management Science Research Report No. 248, Carnegie-Mellon University, under contract N00014-67-A-0314-0007 NR Q47-048 U.S. Navy Office of Naval Research, January, 1972.

46. Shaftel, T. L., Thompson, G. L., "The Continuous Multiple Modular Design Problem," Management Science Research Report No. 254, Carnegie-Mellon University, under contract N00014-67-A-0314-0007 NR 047-048 with the U.S. Office of Naval Research, January, 1972.

47. Stinson, J. P., E. W. Davis, and B. M. Khumawala, "Multiple Resource-Constrained Scheduling Using Branch and Bound," AIIE Transactions, Vol. 10, No. 3, 1978.

48. Talbot, F. B., and J. H. Patterson, "An Efficient Integer Programming Algorithm with Network Cuts for Solving Resource-Constrained Scheduling Problems, "Management Science, Vol. 24, No. 11, 1978.

49. Wiest, J. D., "A Heuristic Model for Scheduling Large Projects with Limited Resources," Management Science, February, 1967.

APPENDIX A

BENCHMARK PROBLEM SPECIFICATIONS
(MarAd Research Contract on Outfit Planning)

I. Introduction

The Maritime Administration currently sponsors research in outfit planning. This research is intended to assist U.S. shipyards in the planning for and scheduling of increased levels of outfitting earlier in the production process. It is described as a "Decision Support System for the Outfit Planning Problem" and is being developed jointly by the Georgia Institute of Technology and the University of Massachusetts.

It is important to the research project that thorough large-scale testing be done on the system under development. Successful testing is viewed as prerequisite to demonstrating the system's utility and effectiveness to the shipbuilding industry. The research team is interested in identifying a project which will serve as a benchmark problem in the testing effort to be conducted in 1980. A general description of the data specifications is developed in the following sections as indicative of the type of data needed.

II. Specification

The general model on which the system is based is the Critical Path Model (i.e. CPM) for activity networks. Thus, outfitting activity relationships are characterized as a CPM activity network with man-hour estimates by category for each activity. These activities and resource estimates represent the essence of the data needed.

A. CPM Activity Network-Outfitting

Event - a discrete point in time denoting the specific starting or ending point for an activity or group of activities.

Activity - the work necessary to progress from one event to another. Activities are operations which consume outfitting time, money or manpower and would generally coincide with the outfit work package or outfit work order (i.e. the work described on a single drawing, or portion thereof, to be done by a single craft in a single geographical area of the ship or shop). Shipyard work orders usually aggregate individual tasks to a level averaging 200-300 man hours, though individual work orders may range from 10 to 2000 man hours.

NOTE: The specification of activities would <u>ideally</u> be at a level of craft man hour loadings more detailed than the work order level. This would allow for the possible division of work order tasks for rescheduling by the system.

Dependencies - the relationship between the activities in a project typically resulting from the precedence of the elements in a production method but also arising from considerations of access and congestion, common equipment requirements by activities or common facilities requirements for activities.

NOTE: These latter types of dependencies reflect the scheduling issues with limited resources devoted to accomplishing the activities. Where possible, these types of dependencies should be separately identified from those due to the requirements of the work method.

B. Network Size

The number of activities in a CPM activity network is frequently used as the measure of the network size. The varied ship production projects of the shipbuilding industry could be viewed in terms of the number of outfitting activities in each. A natural problem that arises for testing is that of one yard's small project being another yard's large project. It is difficult to define the size of the network needed for test purposes since each shipyard's view of an adequate test problem size will likely differ. Therefore the best that can be stated at this time is that the test problem network should be sufficiently large so as to be realistic in the sense of reflecting significant investment in time and materials while engaging various constraining limits such as lifting capacities and craft manpower availability at that shipyard. At the same time, the test problem network should be small enough to be manageable by limited research staff. It is anticipated that the easiest form for data transmission will be magnetic computer tape or computer cards.

C. Auxiliary Information

The decision support system resulting from the research will go beyond the typical CPM system capabilities in terms of decisions reflecting realistic shipyard constraints on resources. The research team can create the auxiliary data needed to test the decision support system in this regard, but the realism of actual shipyard data improves the realism of the testing program. Thus, certain data in addition to the CPM activity network and man hour estimates would be desirable and would enhance the testing.

This data includes the following:

1. On-Unit - "outfitting on-units is the assembly of an interim product consisting of manufactured and purchased components . . .

includes all but final paint coat. Units are composed exclusively of outfit materials and do not incorporate any hull structure."[1] Units are planned for production in such a manner as to gain maximum benefit from a logical work method considering the labor and equipment capabilities in the yard. Where outfit activities are collected into units by the shipyard, data which defines the units in terms of location produced, weight of unit, activities included (along with man-hour estimates per activity),weight added by each activity, and precedence relationships would be very useful.

2. On-Block - "outfitting on-block is the installation of outfit components, perhaps units, onto a hull structural assembly or block prior to its erection."[2] Units, along with additional outfit activities, are often collected and done on-block. Similar information to that associated with unit production, i.e. location of production, weight of block, outfit activities and units included, weight added by each activity and unit and the precedence relationships would be desirable.

3. Maximum Safe Lifting Capacity - a resource that often limits the production process in shipyards in the capacity to lift and hold various units or blocks into place. Thus, for the various locations where unit and block production takes place, data on the maximum safe lifting capacity is needed.

4. Erection Schedule - outfit activities have historically been performed as access to blocks permitted or delayed to be done

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[1]Chirillo, L. D., "Outfit Planning," Draft, pp. 1-5.

[2]Ibid., pp. 1-5.